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Wind Turbine Test

Wind Matic WM 17S

Troels Friis Pedersen

The Test Station for Windmills

Risø National Laboratory, DK-4000 Roskilde Denmark
April 1986

RISØ-M-2546

WIND TURBINE TEST
WIND MATIC WM 17S

Troels Friis Pedersen
The Test Station for Windmills, Risø

Abstract. The report describes standard measurements performed on a Wind-Matic WM 17S, 75 kW wind turbine. The measurements carried out and reported here comprises the power output, system efficiency, energy production, transmission efficiency, rotor power, rotor efficiency, air-brakes efficiency, structural dynamics, loads at cut-in and braking, rotor torque at stopped condition, and noise emission.

EDB-Descriptors: BRAKES; DYNAMIC LOADS; HORIZONTAL AXIS TURBINES; MECHANICAL TESTS; NOISE; PERFORMANCE TESTING; POWER GENERATION; ROTORS.

April 1986
Risø National Laboratory, DK-4000 Roskilde, Denmark.

The wind turbine was tested according to a contract with:
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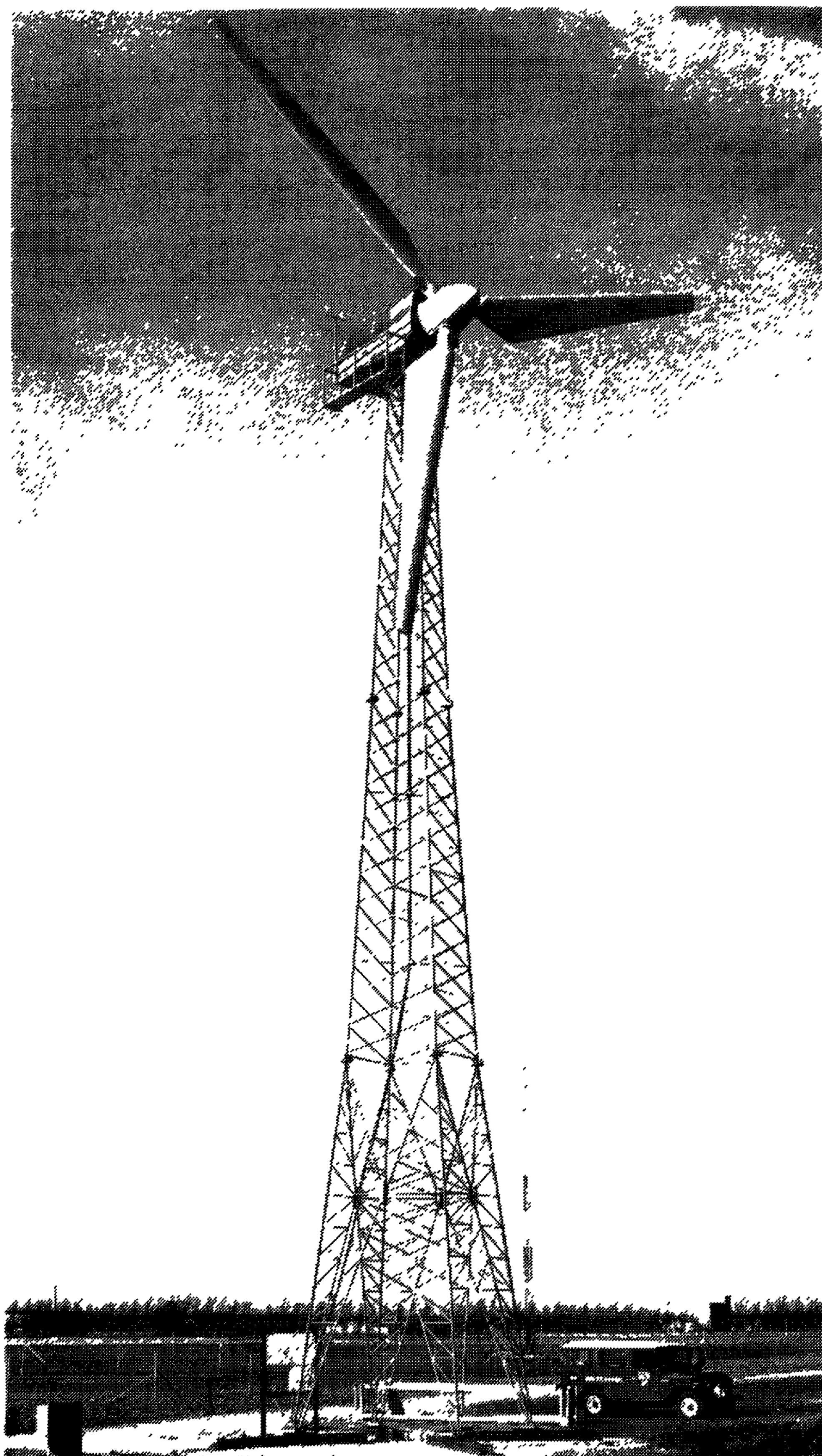


The picture shows the Wind Matic WM 17S erected at the Test Station on stand 3.

CONTENT Page

MOMENCLATURE

A	Scale parameter for a Weibull distribution
C	Form parameter for a Weibull distribution
C_e	Overall turbine efficiency; electric power related to wind power
f	The probability for a wind direction in a certain sector.
LA_{eq}	Equivalent A-weighted sound pressure level
L_p	A-weighted sound pressure level
P_e	Electrical power
V	Wind speed
$\bar{V}$	Annual mean wind speed.

1. INTRODUCTION

The Wind-Matic WM 17S wind turbine was erected at the Test Station in February 1985 on stand 3. The test was completed in December 1985 and the turbine was taken down in January 1986. During the test period the mechanical brake was supplied with three calipers instead of two. The mechanical brake measurements are carried out with three calipers. The measurements made correspond to the standard measurement program, which is developed and carried out at the Test Station for Windmills at Risø. This program is described in refs. 1 and 4.

2. THE WIND TURBINE

In this chapter the wind turbine is described to the extent necessary to understand the measurements carried out. The rotor is surveyed in detail as this is the most important part of the turbine. The principles of the control system are outlined as they are the basis for understanding the safety system and operation of the turbine. Finally, the installation of the sensors on the turbine are sketched. This might aid in interpretating the test results.

2.1 Technical description.

The layout of the nacelle is shown in fig. 2.1.1. The wind turbine has a three-bladed upwind rotor with fixed cantilevered GRP blades on a welded hub, and the rotor is held by two main bearings with a disc brake in between. The gearbox is mounted on the main shaft behind the bearings and two torque stays are led to the machine foundation.

The gearbox and the main generator are connected by a stiff clutch. The two induction generators are mounted on a console with a belt drive between them. Yawing of the nacelle is carried out by an electrical motor controlled by a wind vane, mounted on top of the nacelle. The electrical control system is mounted in a stainless steel box on a frame beside the concrete foundation. The tower is of lattice design, mounted in three sections. Further specifications are listed in table 2.1.2.

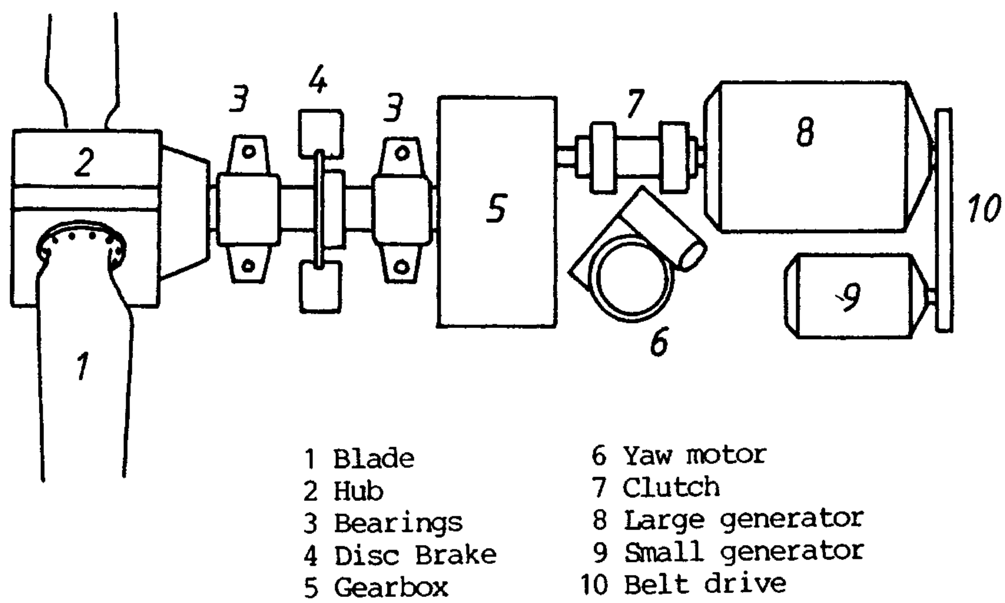


Fig. 2.1.1. Principal lay out of the nacelle.

Table 2.1.2. Technical description of Wind Matic WM 17S

Rotor

Number of blades:	3
Rotor diameter (measured):	16.99 m
Swept area:	226.7 m^2
Rotor rotational speed (measured):	55 rpm and 39 rpm
Tilt:	5^o
Coning:	0^o
Blade tip angle (measured):	1.4^o, 1.1^o and 1.3^o

Blades.

Type: LM-glasfiber 8.5 m cantilevered GRP blades

Blade weight:	320 kg
Spar materiel:	GRP
Shell materiel:	GRP
Blade length:	8.21 m
Root chord:	1.09 m
Tip chord:	0.45 m
Blade twist:	15.0^{0}
Blade profiles:	NACA 63-200-series
Air brakes:	Individual spoiler type, positioned on suction side at about 45% chord.

Gearbox.

Kumera Oy TB 3280 A

Gear ratio:	1:18.7
Gearing ratio between generators:	1:1.42

Generators.

Both generators are asynchronous machines for 50 Hz/380V grid connection.

Primary generator Strømberg

Nominal power (motor):	75 kW
Synchronous rotational speed:	1000 rpm

Secondary generator Strømberg 180 L 48

Nominal power (motor):	15 kW
Synchronous rotational speed:	1000 rpm

Yaw system.

Electric yaw control with wind vane on nacelle and yaw motor

Mechanical brake.

Disc brake with three calipers, mounted on main shaft between main bearings. Hydraulic activation.

Control system.

Electric control system, based on a microprocessor and a thyristor cut-in (see chapter 2.2).

Tower.

Welded, galvanised, lattice tower, type	A. Priess A/S
Number of sections:	3
Tower height	22.34 m

Overall dimensions.

Hub height:	23.04 m
Total height:	31.54 m
Rotor weight (incl. hub):	appr. 1260
Nacelle weight (without rotor):	appr. 4000
Tower weight:	4827 kg
Total weight:	appr. 10100 kg.

2.2 Control system and operation.

The control system is based on a microprocessor, which operates via a number of sensors positioned all over the turbine and a high voltage part, which encloses thyristor "soft cut-in" systems for the generators and contactors for different purposes such as yaw drive and brake activation.

The control system has a full automatic operation mode, where the parameters listed below are supervised, and activation leads to cut-in of the brake. The turbine is not restarted before the failure has been reset.

- grid phase asymmetry
- grid voltage failure
- grid frequency failure
- nacelle vibrations
- brake shoe wear
- gear oil level
- brake oil level
- max yaw time
- overspeed
- failure on large generator relay
- failure on small generator relay
- rotor shaft rpm difference from expected
- large generator shaft rpm difference from expected
- thermistor in large generator
- thermistor in yaw drive
- excess temperature in gearbox
- too many cut-in failures on large generator
- failure at cable twist arrangement

The following parameters leads to temporary stops of the turbine with automatic restart.

- air temperature too low
- thyristor temperature too high
- cable twist too high
- excess power production by large generator
- sensor supply voltage failure
- too high wind speed

The automatic operation is carried out the following way. For wind speeds above and rotor rpm below certain levels automatic motor start is activated. Motor start is controlled in power and stopped before the rotational speed of the small generator is reached. If the wind speed is too high, the rotor accelerates to the rotational speed of the large generator. Otherwise it cuts in on the small generator. When the power production is too high on the small generator it cuts out and accelerates to the large generator. When the power production is too low on the large generator, it cuts out and the small generator is cut in to draw the rotor down in rotational speed.

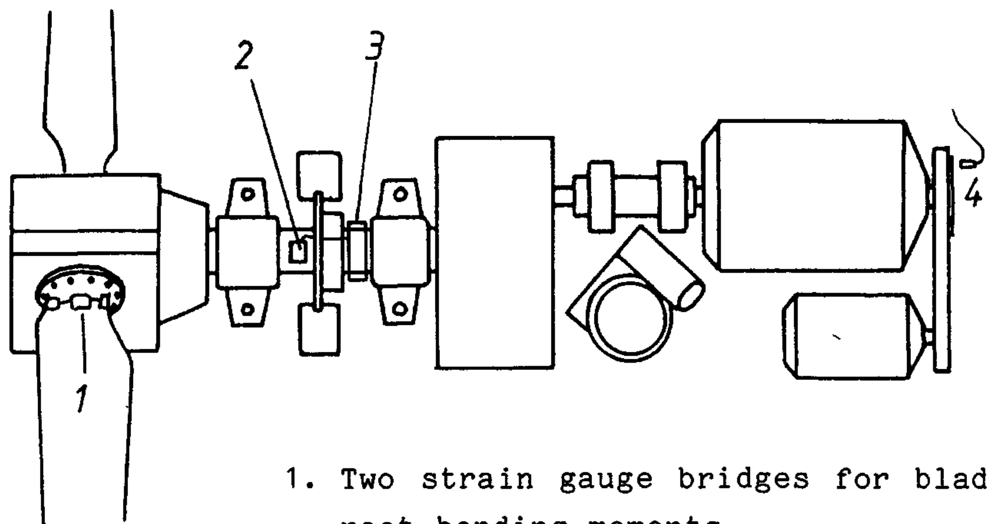
For further information on the operation of the turbine we refer to the operation manual, ref. 3.

A test of the control system has not been carried out. Only the operation of the brake is tested (see chapter 4.1). During the test period the operation of the turbine has been smooth, and the control system seemed to be quite reliable.

2.3 Instrumentation.

This chapter deals with the instrumentation of the wind turbine and the sensors used. The overall instrumentation for standard measurements is shown in chapter 3.2.

At the nacelle, the sensors are mounted according to fig. 2.3.1.



1. Two strain gauge bridges for blade root bending moments
2. Strain gauge bridge for rotor shaft torque
3. One channel FM-transmission equipment
4. Inductive sensor for rotational speed

Fig. 2.3.1. Instrumentation of the nacelle.

One blade was instrumented with two full bridge strain gauge bridges with 360 ohm strain gauges for measurement of flapwise and edgewise bending moments at the root. An 8 channel PCM-transmission equipment with dry batteries was used for bridge supply and data transmission directly to the ground. Data were transmitted as PCM signals to the computer room where they were demultiplexed and converted to analog signals.

On the main shaft between the front bearing and the brake disc a full bridge strain gauge bridge was mounted, also with 360 ohm strain gauges for measurement of shaft torque. A one-channel FM-transmission equipment was mounted close to the strain gauge bridge. This system supplied power to the strain gauge bridge and the data transmission from batteries, but here two coils were mounted around the shaft for the data transmission from the rotating shaft to the nacelle. At the nacelle the signal was converted to an analog signal.

For measuring the rotational speed of the rotor a disc with 9 holes was mounted behind the large generator with an inductive sensor to count the hole frequency.

Close to the sensor a frequency to analog converter was mounted for further data transmission.

The measurement of electric power output was carried out with three current transformers, one on each phase, and a power converter that converts the signal to a voltage signal.

The current is measured with a separate current converter but only on one phase. In this connection uneven loads on the three phases are not taken into account.

Wind speed is measured with a cup anemometer with three cups. The rotor is giving 12 photo electric pulses per rotation and this pulse signal is in another box converted to a voltage signal. The anemometer has been calibrated in a wind tunnel at the Technical University of Denmark, but the calibration was changed due to systematic differencies between this wind tunnel and a 1.8x2.6 m tunnel at Danish Maritime Institute.

The wind direction is measured with a wind vane with a cos/sin resolver. This resolver transmits two voltage signals proportional to the sine and the cosine of the wind direction to the computer room.

Temperature and barometric pressure are measured with two sensors with high accuracy, and they are mounted stationary at the meteorological tower and the computer room accordingly.

3. THE TEST STATION

The conditions for a wind turbine test are very important for the interpretation of the results of the measurements. In the following the conditions for the Test Station are described in chapters comprising the climatological test site, data aquisition and analysis and the load conditions for the turbine.

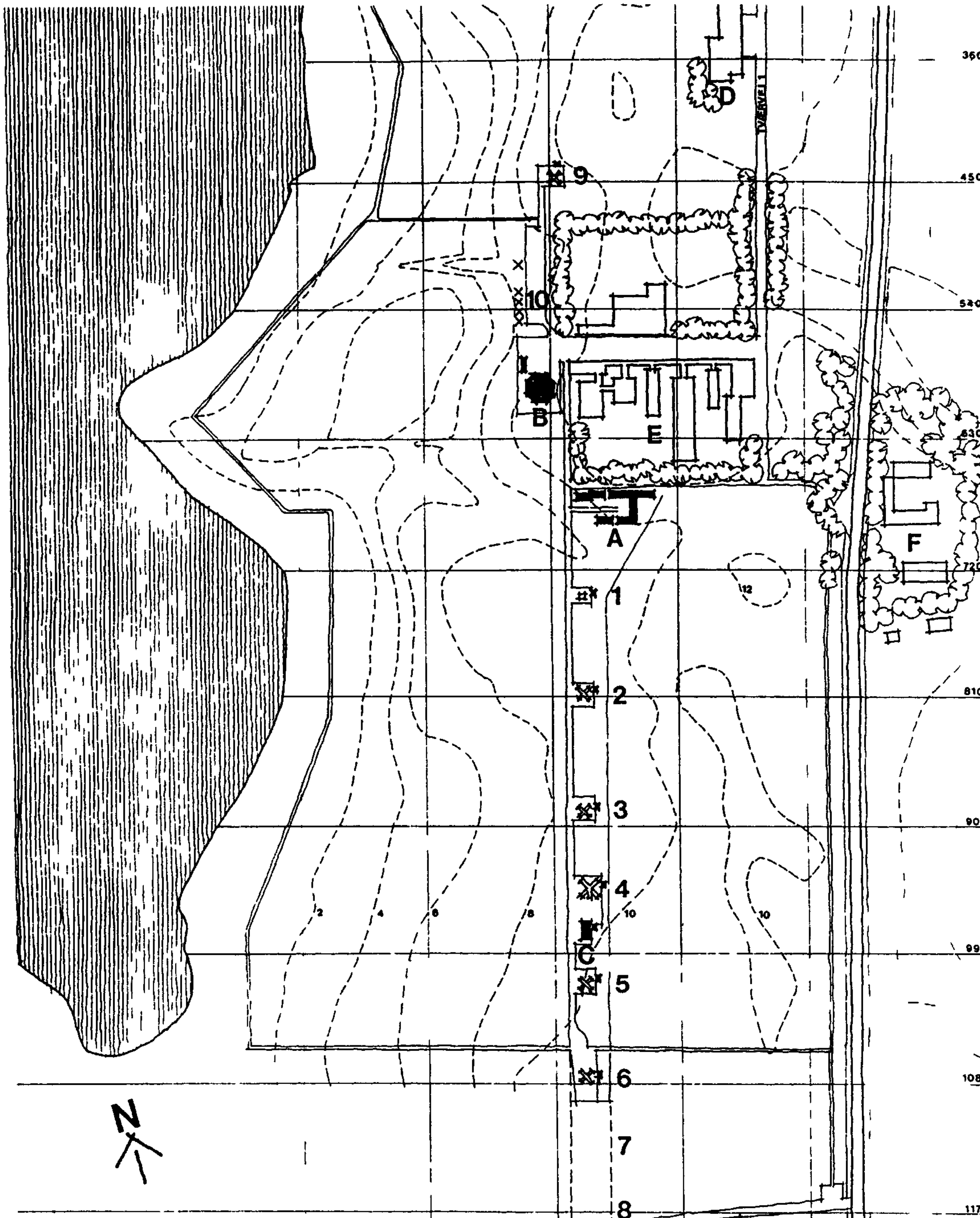
3.1 The test site.

The Test Station for Windmills is situated at Risø National Laboratory, 5 km north of Roskilde, and 30 km west of Copenhagen. The test stands are positioned on a rather flat area close to Roskilde Fjord (see fig. 3.1.1). The prevailing winds are westerly coming from the fjord, and most of the measurements are carried out with this wind direction.

The meteorological conditions at the test site are measured continuously on a central meteorological tower.

The wind speed is measured at 3, 10, 20 and 33 m height, and for the period May 1982 to January 1986 the statistical wind distribution has been calculated.

For the four heights the Weibull parameters for the wind speed distributions are shown in table 3.1.2. Generally the measured distributions fit very well to the Weibull distributions.



<u>Fig. 3.1.1.</u> Topology at the site.

33 m

	A m/s	C	f %	V m/s
N	4.9	1.77	6.0	4.3
NE	4.1	2.04	5.0	3.6
E	6.4	2.10	10.9	5.6
SE	7.1	2.41	17.0	6.3
S	5.5	2.21	9.7	4.8
SV	6.2	2.34	18.2	5.5
V	7.7	2.12	20.6	6.9
NV	6.5	1.68	12.6	5.8
Total	6.5	2.00	100.0	5.7

20 m

	A m/s	C	f %	V m/s
N	4.2	1.75	5.9	3.8
NE	3.4	2.00	4.9	3.0
E	5.7	1.98	10.8	5.0
SE	6.6	2.38	16.9	5.9
S	4.8	2.17	9.6	4.2
SV	5.7	2.26	18.3	5.0
V	7.4	2.13	20.9	6.5
NV	6.3	1.76	12.7	5.6
Total	6.0	1.93	100.0	5.3

10 m

	A m/s	C	f %	V m/s
N	3.8	1.73	5.8	3.4
NE	2.9	1.86	4.8	2.6
E	4.8	1.87	11.9	4.3
SE	5.8	2.25	16.4	5.1
S	4.3	2.03	9.9	3.8
SV	5.4	2.21	18.8	4.7
V	7.1	2.17	19.8	6.3
NV	5.9	1.77	12.5	5.3
Total	5.5	1.87	100.0	4.8

3 m

	A m/s	C	f %	V m/s
N	3.2	1.71	5.6	2.9
NE	2.5	1.75	4.6	2.2
E	3.8	1.66	13.4	3.4
SE	4.7	1.97	16.6	4.1
S	3.5	1.88	9.9	3.1
SV	4.5	2.14	17.3	4.0
V	5.7	2.10	20.2	5.1
NV	4.8	1.80	12.3	4.2
Total	4.4	1.79	100.0	4.0

Table 3.1.2. Weibull parameters for wind speed distributions at the test site.

The annual mean wind speed is 5.3 m/s at 20 m height and 5.7 m/s at 33 m. The prevailing wind directions are shown to be west and southwest, which also are the wind directions used for the measurements on the wind turbines. Stationary masts for wind speed measurements are therefore placed perpendicular to the row of test stands, which has an orientation from 15° north to 195° south. Figure 3.1.3 shows a sketch of the test stands.

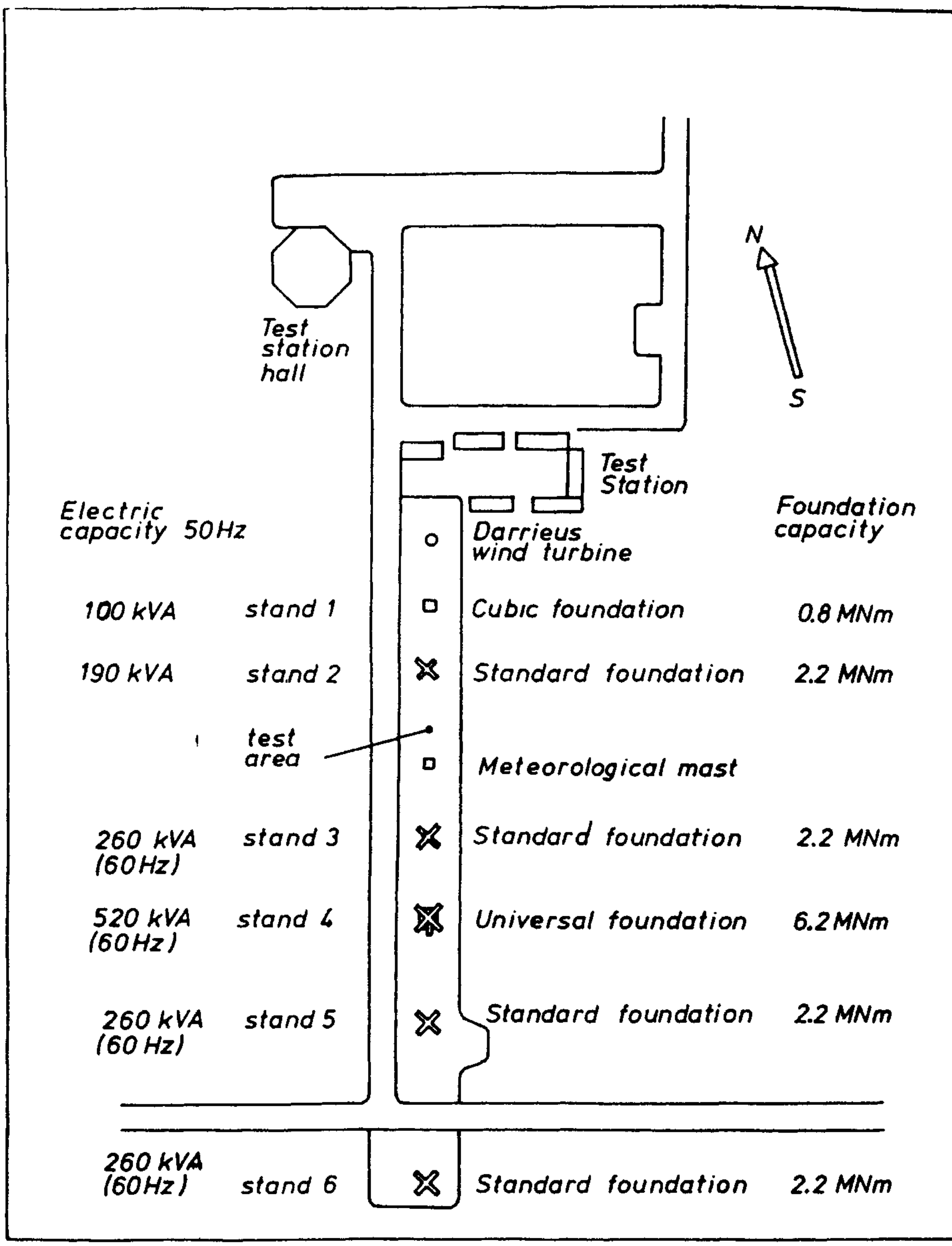


Fig. 3.1.3. The test stands for wind turbine testing.

3.2 Data aquicition and analysis.

The measurement system at the Test Station has multi-channel DC-cables from each test stand to the computer room for transferring data. The sensors are supplied with power from power supplies at each test stand, and the signals are transferred with a voltage range from - 5V to + 5V. Figure 3.2.1 shows the cabling used for the standard measurements.

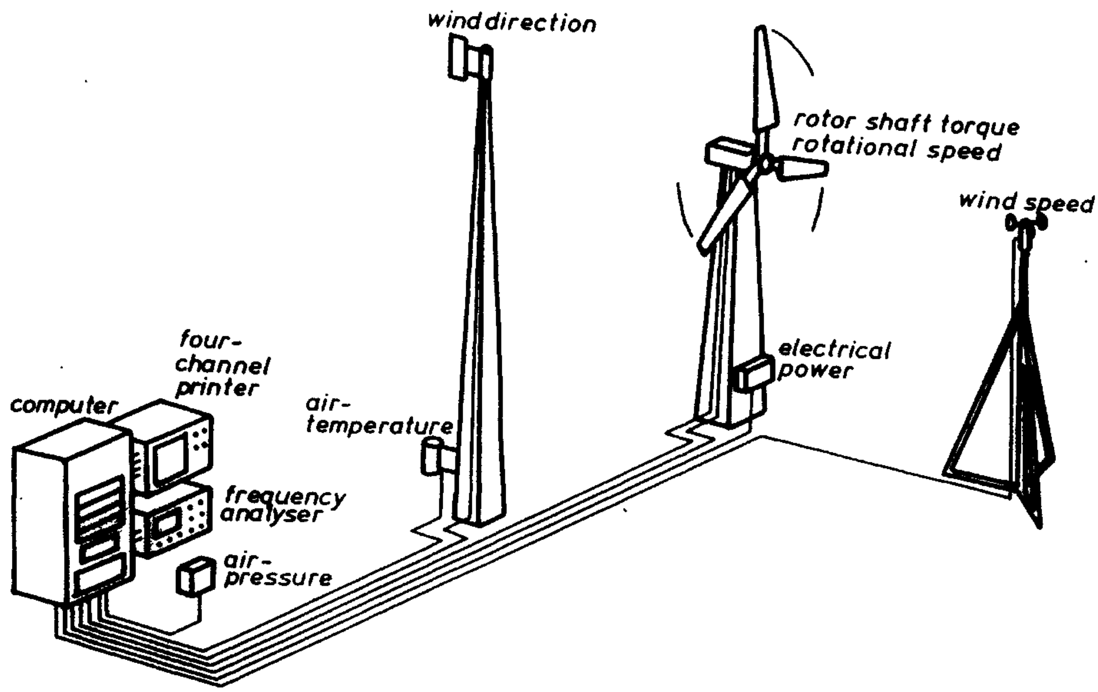


Fig. 3.2.1. Transmission lines used for the standard measurements.

At the computer room all channels pass through a filter that protects the computer equipment from lightning. Afterwards they pass through a low-pass filter module with a cut-off frequency of 0.4 Hz or 20 Hz. Alternatively the signal can pass directly through.

After the filter module the signals can go directly to a strip chart recorder for time-trance recording, to a spectrum analyzer for frequency analyzes or to the computer for data aquisition. Before the computer the analog signals are converted to digital representation with a 12 bit resolution for the ±5V voltage range.

For measurements of power curve, transmission efficiency and air brakes efficiency the 0.4 Hz filter and a sample frequency of 1 Hz is used. The electric power and rotor torque is corrected to a standard air density of 1.225 kg/m^3, corresponding to an air temperature of 15° C and barometric pressure of 1013.3 mbar. This is in accordance with the IEA-recommendation (ref. 2).

The sampled data are averaged over 30 seconds and 10 minutes. Data analysis is now performed using the Method of Bins with a bin width of 0.5 m/s. The centers of the bins are each at half and full m/s. For each bin the wind speed, electric power, rotor rotational speed and rotor torque is averaged and for electric power and rotor torque the standard deviation is calculated.

For power curve measurements only at 90° sector from 240° at southwest to 330° at north west is included in the data analysis and the data shall contain at least 200 hours of 10 minutes average data, and only bins with more than 3 averages are included. The power curve is extended by 30-sec averages at higher wind speeds, but only for at least 3 averages. It is pointed out that data from the 30 sec averages are based on far fewer operating hours, and the accuracy of these data is correspondingly lower.

Correction for wind shear is not performed as the wind speed sensor is positioned at hub height at a distance of minimum two rotor diameters from the wind turbine and maximum four rotor diameters from it.

For measurements on air brakes 30-sec average data are used but with a 120° sector.

3.3 The load for the turbine.

The turbine was tested on a 50 Hz, 3 x 380 V grid, which was connected to a 350 kW transformer raising the voltage level to

10 kV. At the time of the testing all turbines in the test row were connected to the same transformer (see Fig. 3.1.3).

4. SAFETY TESTS

A windmill has one or more safety systems with the purpose of keeping the turbine from overloading in emergency situations. Testing of these systems is therefore important to insure safe operation. In this chapter the measurements are reported on the mechanical and air brakes.

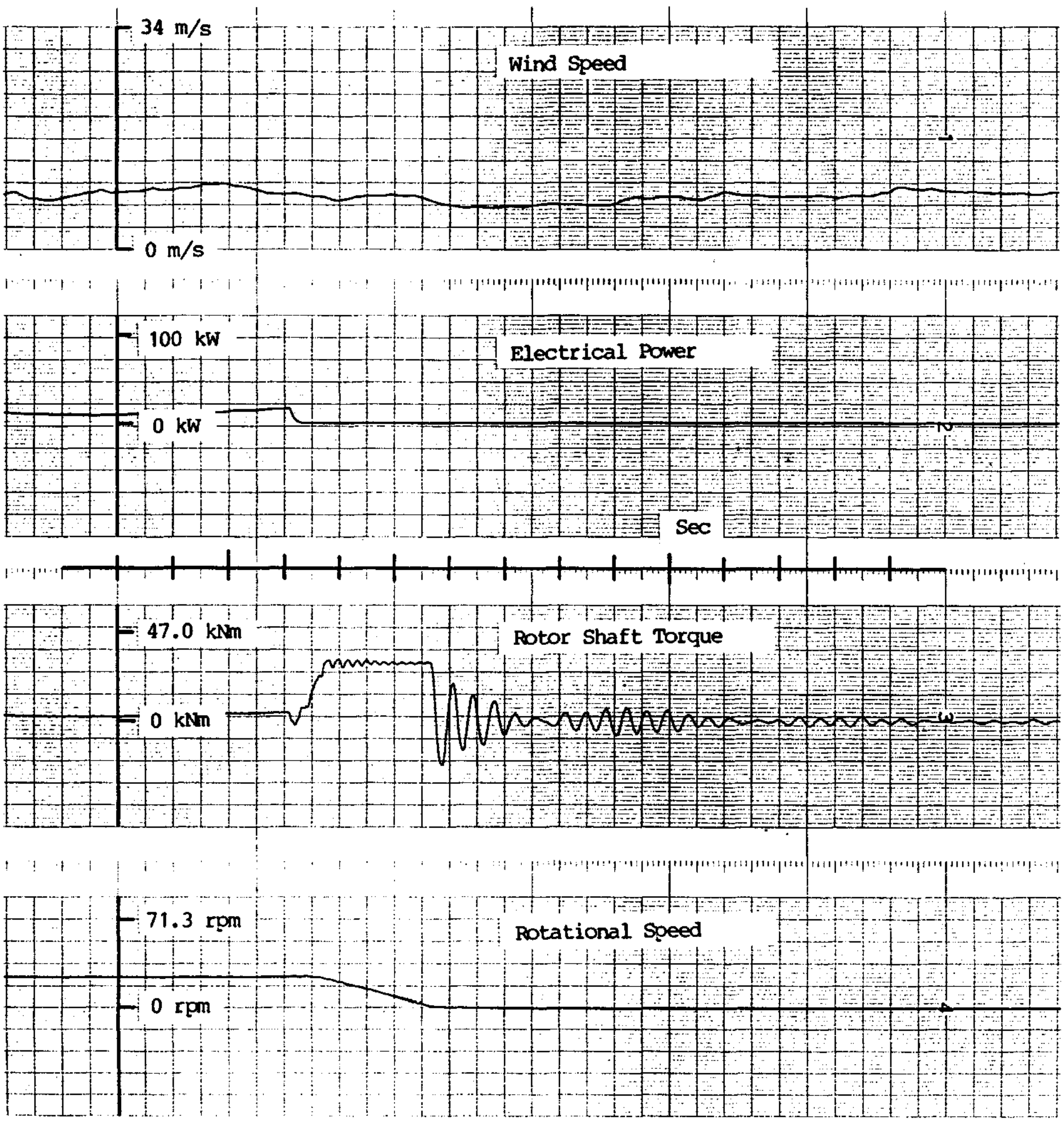
4.1 Test of mechanical brake.

The mechanical brake was tested in two ways. The loads at normal stop, where the "STOP" button is pressed, were recorded and afterwards they were measured by disconnecting the main switch to the grid.

Figure 4.1.1 shows the result of a normal stopping procedure. The power was approximately 20 kW on the large generator when the "STOP" button was activated. It is seen that the brake torque increases to full torque in about 0.6 sec. No transients are seen at the cut-in of the brake. At cut-out of the generator, which seems to be at the same time as cut-in of the brake, a drop in torque is noted. The brake torque is kept rather constant at 30.4 kNm throughout the stop sequence. When stopped, the rotor oscillates at a frequency of 2.7 Hz and the damping in the system brings it to a full stop in about 20 cycles. The stopping procedure was repeated four times and the result was the same each time.
The braking sequence by disconnecting the main switch for the grid is shown in figure 4.1.2. The power was about 63 kW when the large generator was cut-out. A very small acceleration of the rotor is seen while the brake torque builds up. A drive train eigenfrequency of 4.3 Hz is seen during this phase. Full brake torque is reached 0.58 sec after cut-out of the genera-

Wind Matic WM17S

Activation of Mechanical Brake



Brake is activated by pushing the 'STOP'-button
on the control system.
Measurement period: 1-Aug-85

TURBINE DATA

Rotor diameter: 16.99 m
Swept area: 226.7 m**2

Rotational speed: 39 rpm and 55 rpm
Tip angle: 1.4, 1.1 and 1.3 deg

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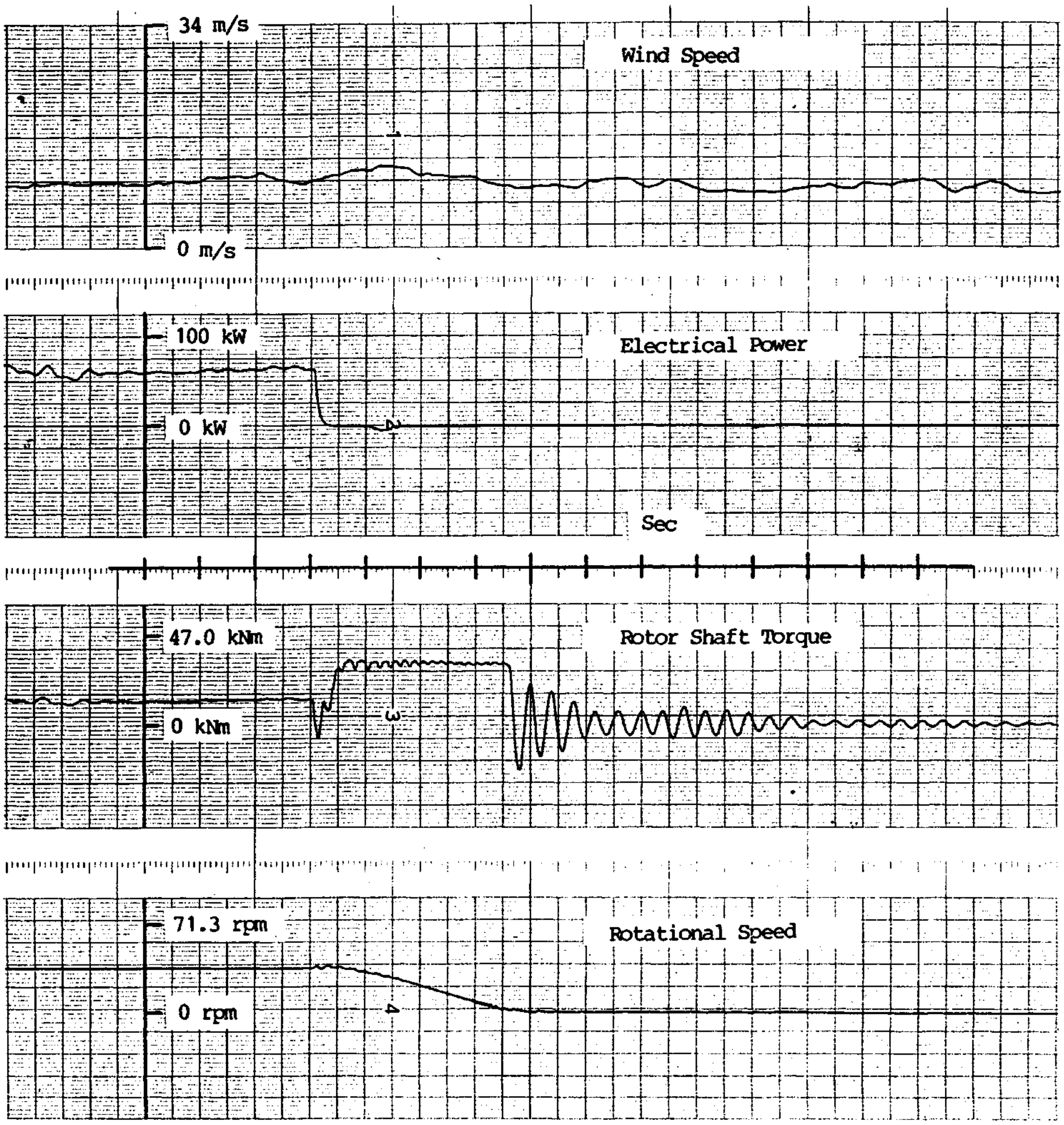
Fig. 4.1.1 Mechanical brake ("STOP" button)

Wind Matic WM17S

Activation of Mechanical Brake



Brake is activated by disconnecting the main switch for the grid.
Measurement period· 3–Dec–85

TURBINE DATA

Rotor diameter· 16.99 m	Rotational speed· 39 rpm and 55 rpm
Swept area· 226.7 m**2	Tip angle· 1.4, 1.1 and 1.3 deg

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Drawn: 12–DEC–85 Report: RISO–M–2546

Fig. 4.1.2 Mechanical brake. (Main switch).

tor and no torque peak is seen. The drive train oscillations are damped out, and afterwards the brake torque is constantly 31.4 kNm.

The brake torque of 31.4 kNm is 2.10 times that of the torque at 73 kW electric power and 55 rpm.

4.2 Test of air brakes.

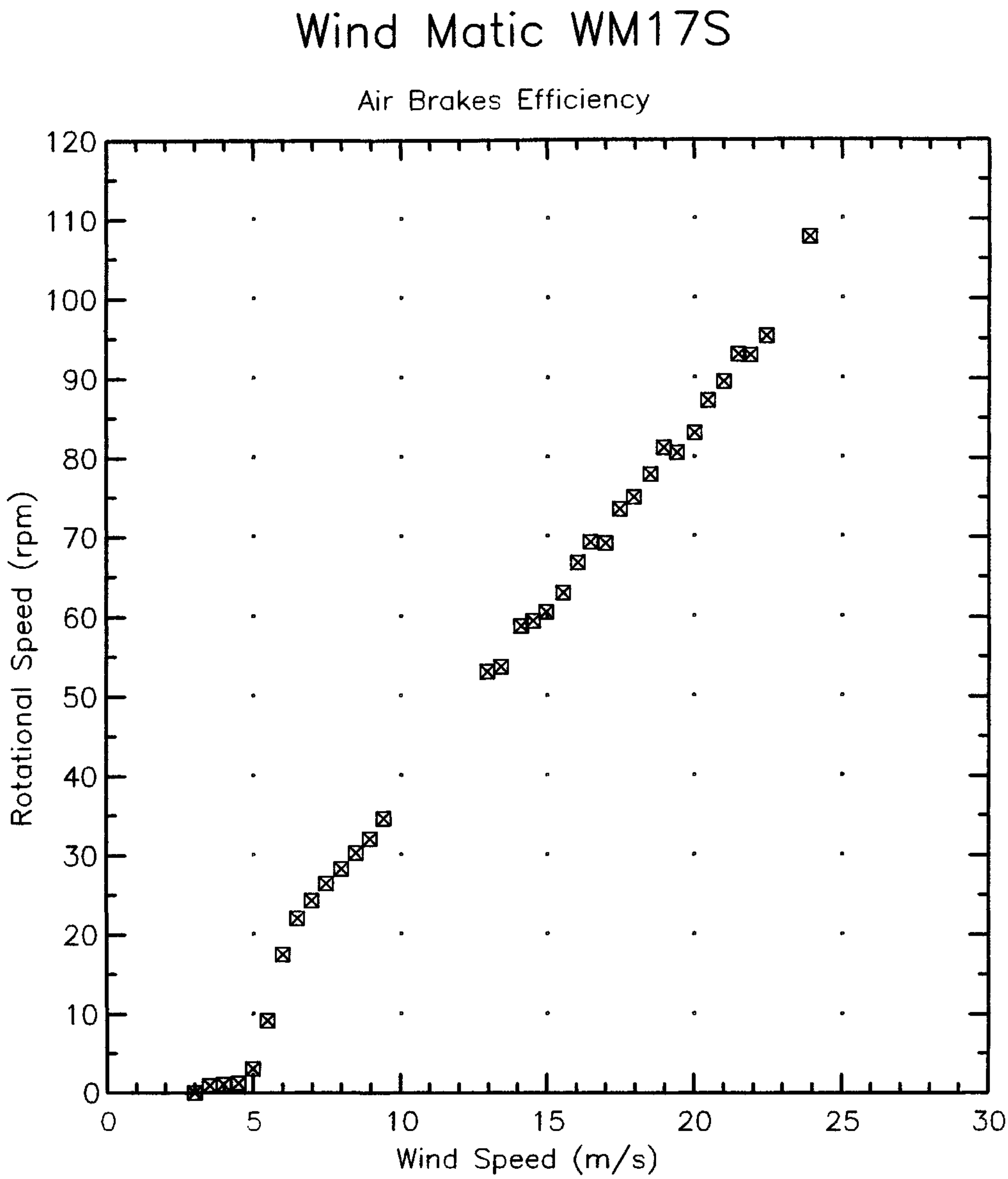
The air brakes were tested in August and September 1985 in three runs. At lower wind speeds only two spoilers were activated due to a small acceleration of the rotor. In a 17 m/s wind all three spoilers were activated simultaneously at 20% overspeed, and stayed opened in a fixed position throughout the measurement period.

The efficiency of the air brakes was measured during three periods, totalling almost 27 hours. The data were averaged over 30 sec. and data reduction was carried out with the method of bins. The result is shown in fig. 4.2.1 and tabulated in table 4.2.2.

The result is a rather linear relationship between wind speed and rotational speed. At wind speeds below 6 m/s the rotor simply stops. At higher wind speeds the gain in rotational speed is 4.7 rpm per m/s with an offset of -9 rpm. The normal rotational speed is reached at 13.6 m/s. At 30 m/s the rotational speed is 83 rpm, An extrapolation of the curve indicates rational speeds of 132 and 179 rpm at 30 and 40 m/s respectively.

These rotational speeds are very high and therefore special precautions must be taken at sites with extremely high wind speeds.

It is recommended than an effort is made to develop more efficient air brakes.



Data origin· Measurement
Measurement period 23–Aug–85 to 6–Sep–85
Total measurement time 26 6 Hours

TURBINE DATA

Rotor diameter 16 99 m
Swept area 226 7 m**2
Rotational speed 39 rpm and 55 rpm
Tip angle 1.4, 1.1 and 1.3 deg

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Fig. 4.2.1. Efficiency of air brakes.

Table 4.2.2. Efficiency of air brakes.

Wind Matic WM17S RISO-M-2546

ROTOR DIAMETER (M): 16.99 m
SWEPT AREA (M**2): 226.7 m**2
ROTATIONAL SPEED (RPM): 39 rpm and 55 rpm
TIPANGLE (DEG): 1.4, 1.1 and 1.3 deg
MEASUREMENT PERIOD: 23-Aug-85 to 6-Sep-85
MEASUREMENT TIME: 26.6 Hours

MEASURED DATA CURVE: Air Brakes Efficiency

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3 Active Spoilers

X: Wind Speed (m/s)
Y: Rotational Speed (rpm)

	X	Y
1	3.00	0.030
2	3.52	0.870
3	3.99	1.050
4	4.50	1.180
5	4.99	3.030
6	5.49	9.230
7	5.99	17.530
8	6.49	22.110
9	6.99	24.320
10	7.48	26.440
11	7.99	28.350
12	8.48	30.320
13	8.96	32.050
14	9.43	34.660
15	12.96	53.150
16	13.44	53.780
17	14.12	58.860
18	14.53	59.520
19	14.97	60.630
20	15.56	63.060
21	16.06	66.800
22	16.48	69.320
23	17.00	69.170
24	17.48	73.500
25	17.96	75.000
26	18.52	77.900
27	18.97	81.260
28	19.42	80.660
29	20.01	83.120
30	20.46	87.170
31	21.01	89.600
32	21.49	93.020
33	21.89	92.940
34	22.45	95.330
35	23.92	107.760

5. PERFORMANCE MEASUREMENTS

The performance of the wind turbine is an important measurement because the economy is to a large extent based on the ability of the turbine to produce power.

Turbine efficiency, transmission efficiency, rotor power and rotor efficiency are important in that they indicate how power is generated and lost in the transmission to useful power.

5.1 Power Curve Measurements.

The power curve was measured in a period from 22.4.1985 to 9.9.1985. In the period 20 runs were carried out with wind from the westerly wind sector. These runs are tabulated below.

Table 5.1.1 Measurement periods for power curve.

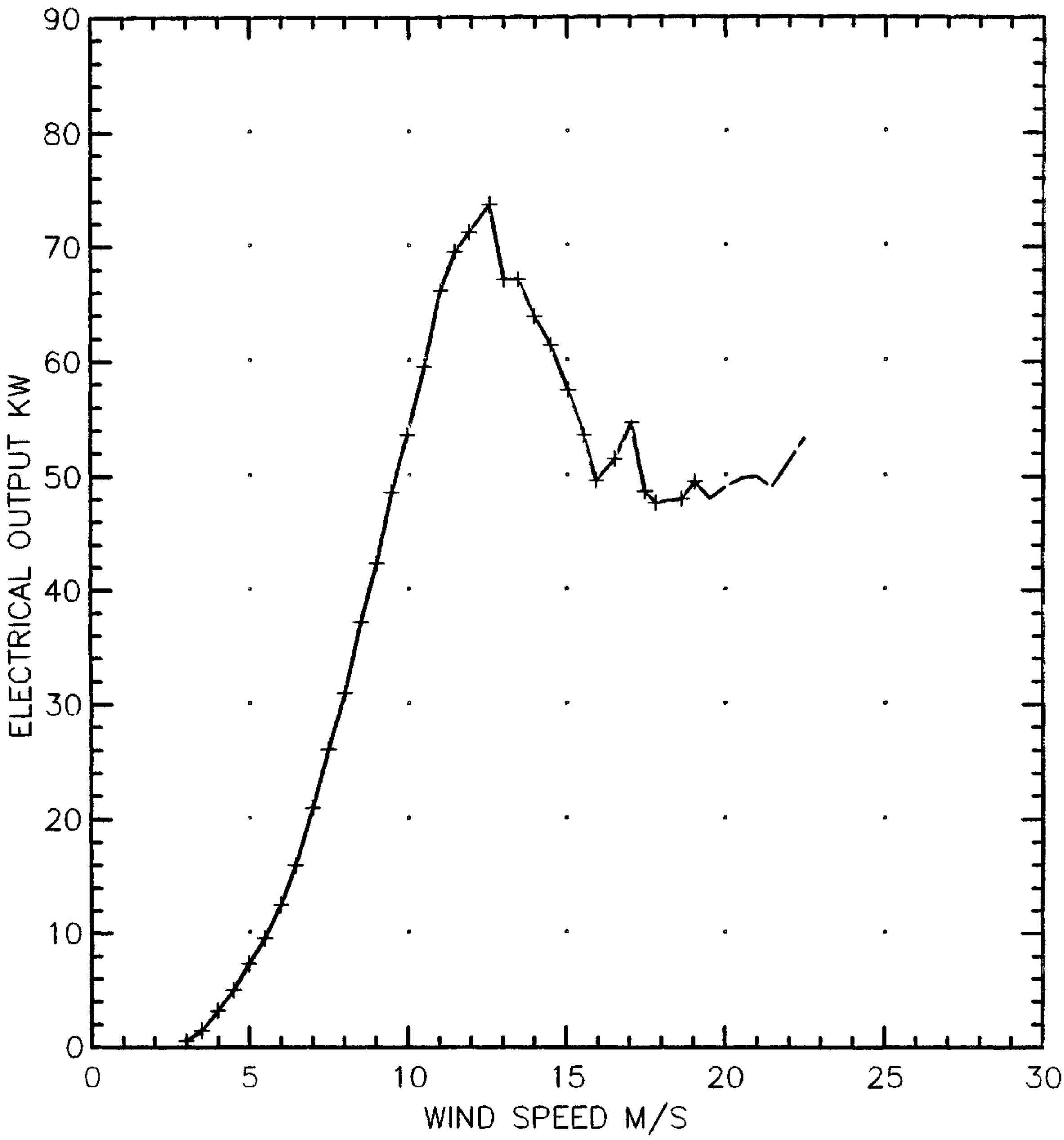
date	hours	Average for the measurement period wind speed m/s	turb. intensity	air pressure mBar	air temp. deg.	air density kg/m^3
22.04-85	6	7.3	0.150	1015	4	1.275
24.04	6	8.1	0.121	1017	6	1.269
07.06	60	6.4	0.167	1007	11	1.234
11.06	6	8.3	0.133	1010	13	1.229
11.06	14	4.0	0.15	1008	10	1.238
15.06	30	5.5	0.169	1008	11	1.236
20.06	16	3.3	0.120	1012	15	1.225
24.06	16	3.0	0.118	1013	15	1.224
26.06	24	2.7	0.159	1015	14	1.233
27.06	20	5.1	0.128	1011	14	1.227
28.06	60	5.2	0.155	1013	14	1.229
01.07	6	9.3	0.128	1012	15	1.224
01.07	16	7.0	0.114	1013	14	1.228
02.07	18	3.5	0.115	1021	15	1.233
05.07	70	5.2	0.166	1021	16	1.231
10.07	18	4.7	0.114	1017	16	1.224
19.07	24	4.9	0.170	1009	2	1.278
04.09	20	9.8	0.122	1012	13	1.232
06.09	70	11.5	0.104	1009	12	1.233
09.09	8	6.2	0.087	1017	11	1.246

The data from these runs are corrected to a standard air density of 1.225 kg/m^3 and averaged. The power curve is shown in fig. 5.1.2. with 30 sec average data as a dashed line.

In table 5.1.3 the power and the turbine efficiency curves are tabulated. 30 sec average data are shown in parenthesis. The wind turbine efficiency is shown in fig. 5.1.4.

Wind Matic WM17S

Electrical Power Curve



Data origin Measurement
Measurement period 22-Apr-85 to 9-Sep-85
Total measurement time 315 5 Hours
Data reduction Method of bins, 10 min averaging time

TURBINE DATA

Rotor diameter 16 99 m | Rotational speed 39 rpm and 55 rpm
Swept area 226 7 m**2 | Tip angle 1 4, 1 1 and 1 3 deg

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Fig. 5.1.2. Measured power curve.

Table 5.1.3. Measured power curve.

WIND TURBINE: Wind Matic WM17S REPORT: RISO-M-2546

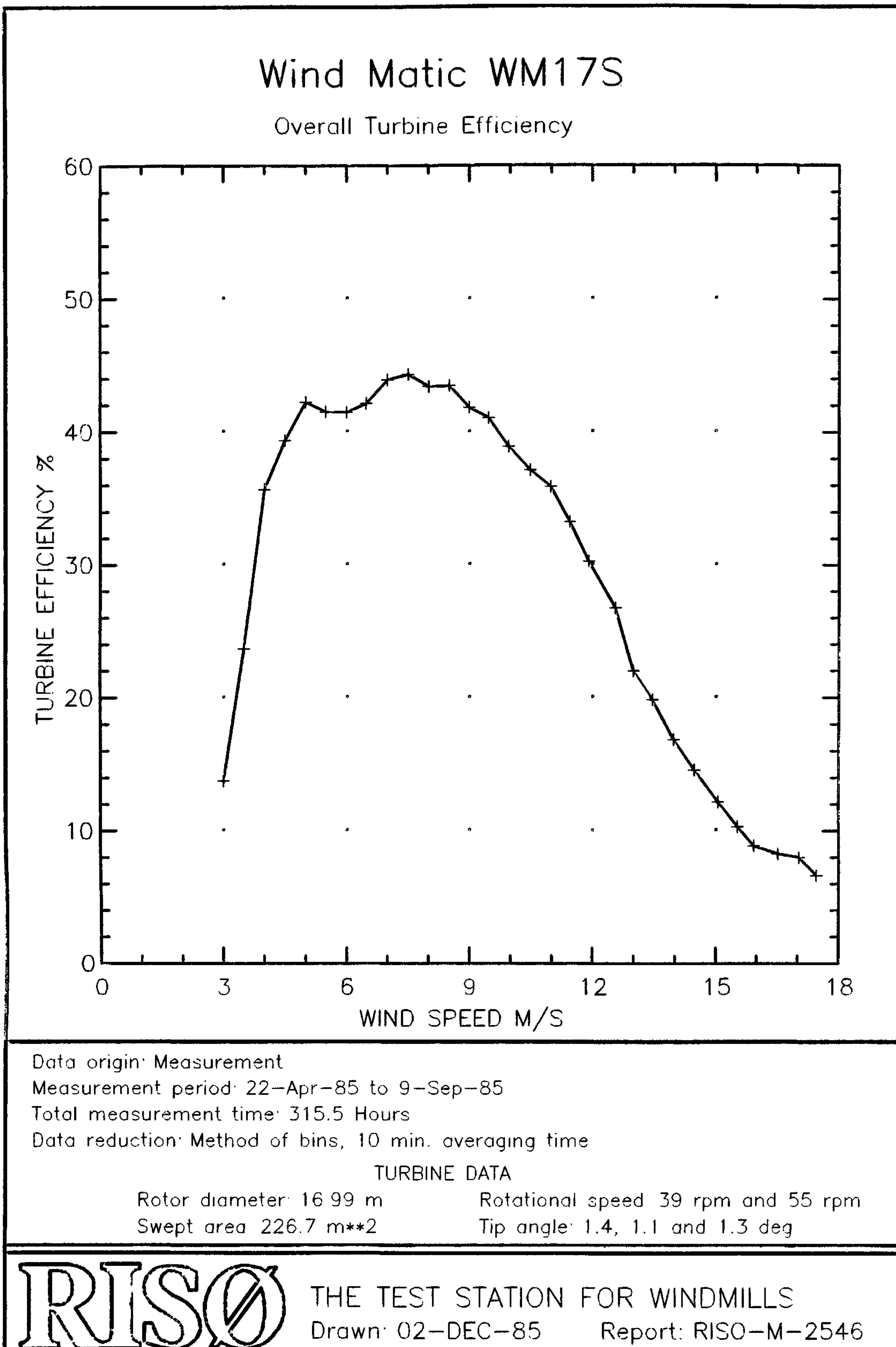
ROTOR DIAMETER: 16.99 m
SWEPT AREA: 226.7 m**2
ROTOR SPEED: 39 rpm and 55 rpm
TIP ANGLE: 1.4, 1.1 and 1.3 deg
MEASUREMENT PERIOD: 22-Apr-85 to 9-Sep-85
MEASUREMENT TIME: 315.5 Hours

MEASURED POWER CURVE

MEASUREMENTS ARE BASED ON 10-MIN. AVERAGES
DATA IN PARENTHESIS ARE BASED ON 30-SEK AVERAGES

	WIND SPEED m/s	mph	EL. POWER kW	AVERAGES NO.	OVERALL EFFICIENCY
1	2.99	6.69	0.510	61	0.137
2	3.50	7.83	1.410	88	0.237
3	4.00	8.95	3.170	117	0.357
4	4.50	10.07	4.980	141	0.394
5	5.00	11.19	7.330	135	0.422
6	5.49	12.28	9.540	171	0.415
7	6.01	13.45	12.500	115	0.415
8	6.48	14.50	15.930	138	0.422
9	7.00	15.66	20.910	128	0.439
10	7.51	16.80	26.070	88	0.443
11	8.01	17.92	30.980	95	0.434
12	8.51	19.04	37.210	125	0.435
13	9.00	20.14	42.370	116	0.419
14	9.48	21.21	48.600	78	0.411
15	9.97	22.31	53.580	60	0.389
16	10.49	23.47	59.530	38	0.371
17	10.99	24.59	66.190	28	0.359
18	11.46	25.64	69.540	22	0.333
19	11.92	26.67	71.240	16	0.303
20	12.56	28.10	73.670	6	0.268
21	13.00	29.09	67.110	9	0.220
22	13.46	30.12	67.150	16	0.198
23	13.98	31.28	63.900	18	0.168
24	14.48	32.40	61.390	14	0.146
25	15.05	33.67	57.500	11	0.121
26	15.53	34.75	53.560	18	0.103
27	15.93	35.64	49.630	7	0.088
28	16.52	36.96	51.480	15	0.082
29	17.03	38.10	54.680	5	0.080
30	17.46	39.07	48.680	7	0.066
31	17.81	39.85	47.650	1	0.061
32	18.63	41.68	47.980	3	0.053
33	19.02	42.56	49.520	3	0.052
34	(19.51)	(43.65)	(48.020)	(70)	(0.047)
35	(19.98)	(44.70)	(49.040)	(58)	(0.044)
36	(20.50)	(45.87)	(49.810)	(25)	(0.042)
37	(20.95)	(46.87)	(49.960)	(28)	(0.039)
38	(21.43)	(47.95)	(49.000)	(14)	(0.036)
39	(21.98)	(49.18)	(51.270)	(6)	(0.035)
40	(22.46)	(50.25)	(53.270)	(3)	(0.034)

STOP WIND SPEED (M/S): 25.0



<u>Fig. 5.1.4.</u> Wind turbine efficiency.

The wind turbine starts production at 3 m/s and at 7.5 m/s it reaches the maximum efficiency of 44.3% at 26.10 kW. Nominal power is not reached, but at 12.5 m/s the maximum power is 73.7 kW. The stall regulation decreases the power output to about 47 kW at a wind speed of about 18 m/s. Highest 30-sec average wind speed was measured at 22.5 m/s where the power output was 53.3 kW. The stop wind speed of 25 m/s was not reached.

5.2. Annual Energy production.

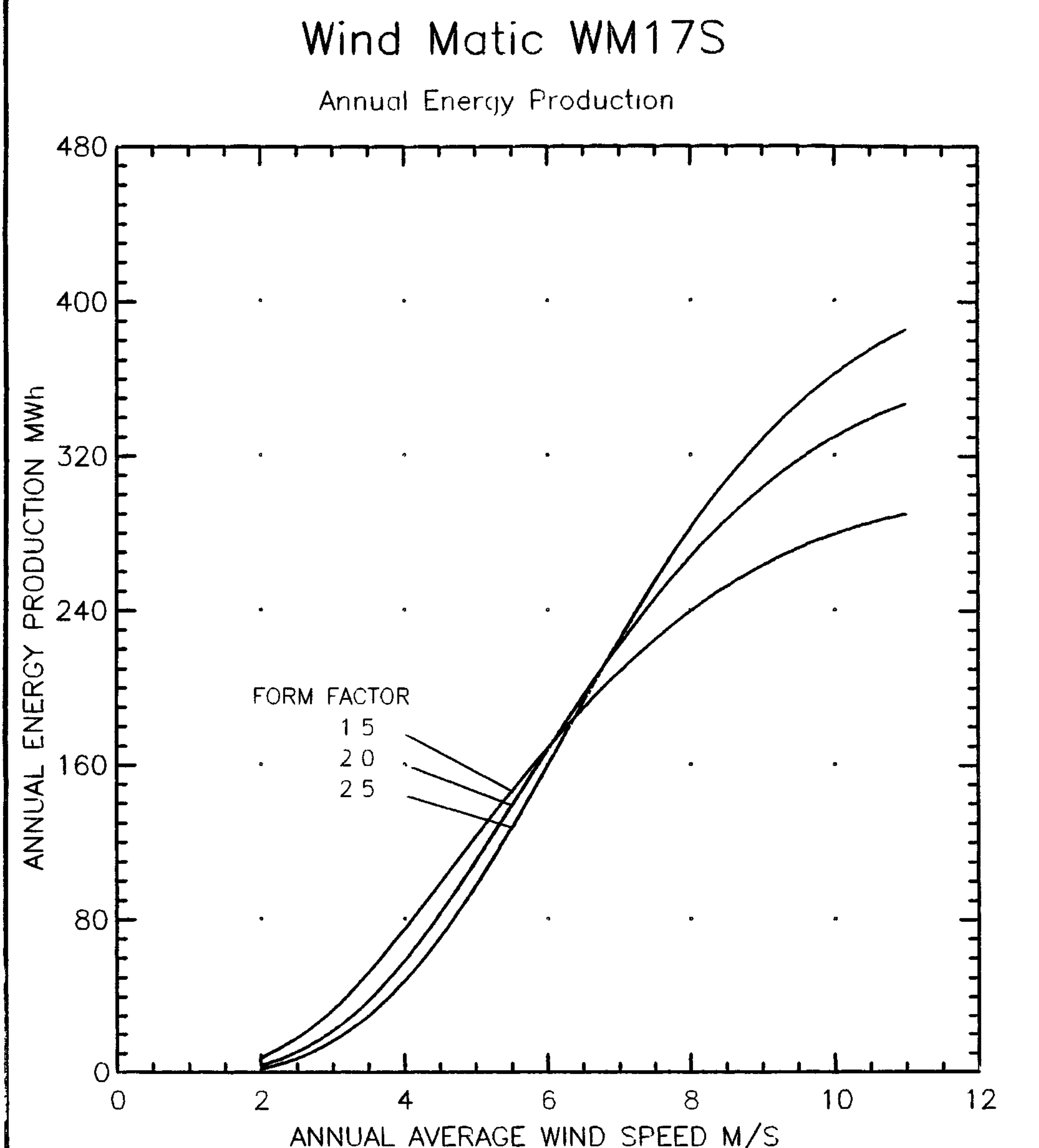
Annual energy production is calculated for a 100% availability and with the power curve data from chapter 5.1. The power output between the highest measured wind speed and the stop wind speed is considered the same as at the highest measured wind speed.

Calculation of the annual energy production is based on Weibull distributions, which for a form factor of two equals the Reyleigh distribution (see ref. 1). The calculation is divided into two different categories. One deals with world-wide application, where the annual mean wind speed is related to the hub height and five different form factors. For other form factors the annual energy production can be interpolated between the data given in fig. 5.2.1 and table 5.2.2.

For Danish application the Wind Atlas method is used (see ref. 5). The annual energy production is calculated for the four clean roughness classes 0, 1, 2 and 3 at a wide range of hub heights and the data is presented in table 5.2.3. For the actual 22 m hub height of the tested wind turbine, the annual energy production at roughness class 0 is calculated as 247 MWh and correspondingly for class 1, 2 and 3 to 183, 145 and 87 MWh.

For a specific site the terrain should be divided into eight direction sectors and analyzed separately as showed in the Wind Atlas. For other wind speed distributions than the Weibull distribution a specific calculation must be made.

A summary of the performance measurements is shown in fig. 5.2.4.



TURBINE DATA

Rotor diameter 16 99 m — Rotational speed 39 rpm and 55 rpm

Swept area 226 7 m**2 — Tip angle 1 4, 1 1 and 1 3 deg

The annual energy production is calculated on basis of a measured power curve Stop wind speed is 25 0 m/s
A 100% availability of the turbine is assumed

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Fig. 5.2.1. Energy production for different mean wind speeds and form factors.

Table 5.2.2 Energy production for different average wind speeds and form factors.

WIND TURBINE: Wind Matic WM17S REPORT: RISO-M-2546

ANNUAL ENERGY PRODUCTION

AV. WIND SPEED		FORM FACTORS				
		1.50	1.75	2.00	2.25	2.50
m/s	mph	(KWH)	(KWH)	(KWH)	(KWH)	(KWH)
2.0	4.5	7,760	5,289	3,749	2,719	1,999
2.5	5.6	18,093	13,617	10,721	8,734	7,287
3.0	6.7	33,248	26,612	22,054	18,883	16,593
3.5	7.8	52,592	44,299	38,029	33,465	30,123
4.0	8.9	74,912	66,095	58,569	52,658	48,146
4.5	10.1	98,816	90,881	83,062	76,269	70,730
5.0	11.2	123,063	117,296	110,399	103,596	97,531
5.5	12.3	146,698	144,045	139,209	133,474	127,706
6.0	13.4	169,062	170,089	168,154	164,492	159,990
6.5	14.5	189,738	194,700	196,133	195,269	192,909
7.0	15.7	208,490	217,419	222,373	224,676	225,053
7.5	16.8	225,215	237,998	246,405	251,922	255,293
8.0	17.9	239,897	256,326	267,999	276,558	282,870
8.5	19.0	252,584	272,386	287,086	298,404	307,388
9.0	20.1	263,367	286,223	303,691	317,458	328,746
9.5	21.3	272,366	297,923	317,893	333,822	347,035
10.0	22.4	279,715	307,599	329,798	347,640	362,452
10.5	23.5	285,557	315,385	339,528	359,064	375,226
11.0	24.6	290,036	321,423	347,217	368,244	385,572

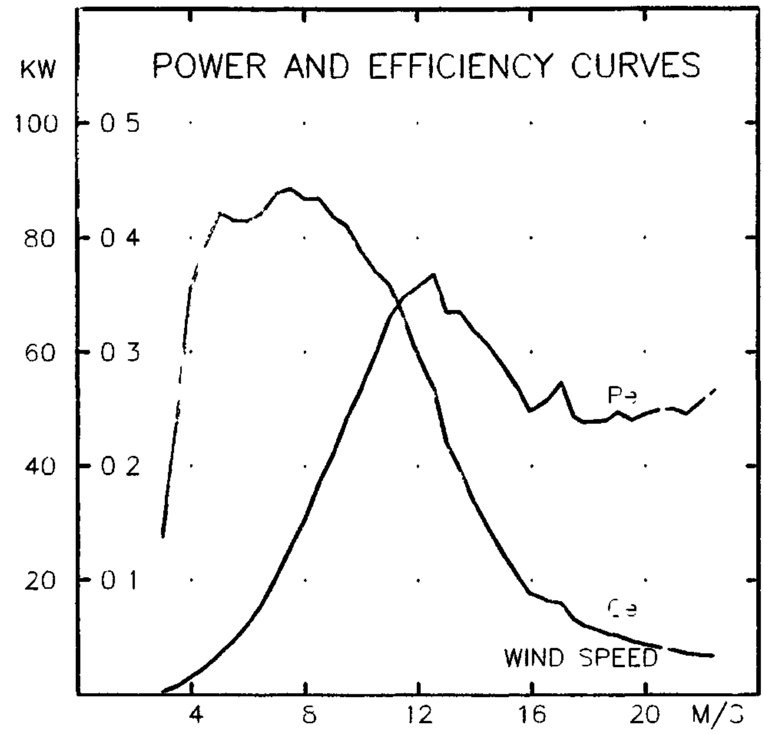
Table 5.2.3. Energy production for different roughness classes and hub heights.

WIND TURBINE: Wind Matic WM17S REPORT: RISO-M-2546

ANNUAL ENERGY PRODUCTION

ROUGHNESS CLASS	0	1	2	3
HUB HEIGHT (M)	(KWH)	(KWH)	(KWH)	(KWH)
18	241,530	173,067	133,970	76,203
19	243,151	175,815	137,012	79,213
20	244,677	178,420	139,908	82,107
21	246,118	180,896	142,670	84,895
22	247,482	183,255	145,310	87,583
23	248,775	185,506	147,838	90,178
24	250,006	187,659	150,263	92,687
25	251,178	189,722	152,592	95,113
26	252,405	191,902	155,012	97,654
27	253,578	193,995	157,342	100,118
28	254,702	196,005	159,587	102,509
29	255,781	197,939	161,752	104,830
30	256,817	199,803	163,844	107,085

Wind Matic WM17S



V (M/S)	Pe (KW)	Ce
2.99	0 51	0 137
3.50	1.41	0 237
4.00	3.17	0 357
4.50	4.98	0 394
5.00	7.33	0 422
5.49	9 54	0 415
6 01	12.50	0 415
6 48	15.93	0 422
7.00	20 91	0 439
7.51	26.07	0 443
8 01	30 98	0 434
8 51	37.21	0 435
9 00	42.37	0 419
9 48	48 60	0 411
9 97	53.58	0 389
10 49	59 53	0 371
10 99	66 19	0 359
11.46	69 54	0 333
11.92	71.24	0 303
12.56	73.67	0 268
13.00	67.11	0 220
13.46	67.15	0 198
13.98	63.90	0 168
14.48	61.39	0 146
15.05	57.50	0 121
15.53	53.56	0 103
15.93	49 63	0 088
16 52	51.48	0 082
17.03	54.68	0 080
17.46	48 68	0 066
17.81	47.65	0 061
18 63	47.98	0 053
19 02	49 52	0 052
(19 51)	(48.02)	(0 047)
(19 98)	(49 04)	(0 044)
(20 50)	(49 61)	(0 042)
(20 95)	(49 96)	(0 039)
(21.43)	(49 00)	(0 036)
(21.98)	(51.27)	(0 035)
(22.46)	(53.27)	(0 034)

VSTOP= 25.0 M/S

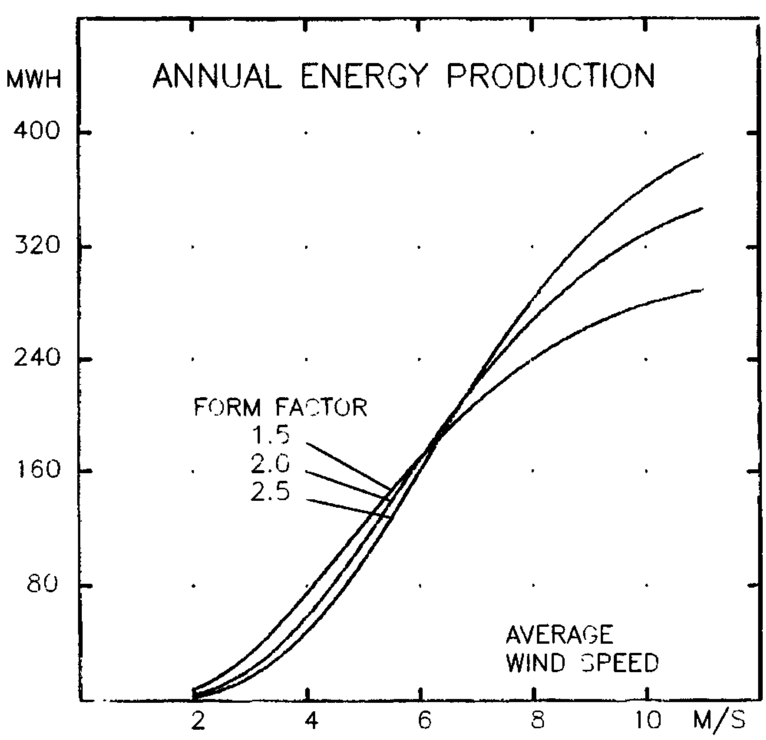


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Fig. 5.2.4. Summary of performance measurements.

5.3 Transmission efficiency

The power train idling for motor without the rotor was measured in the Test Station's workshop.

At first, the small generator was coupled to the grid, and the absorbed power for cold condition was 2.7 kW. When the power was constant the absorbed power was 1.8 kW and the gearbox oil temperature 23 deg(C).

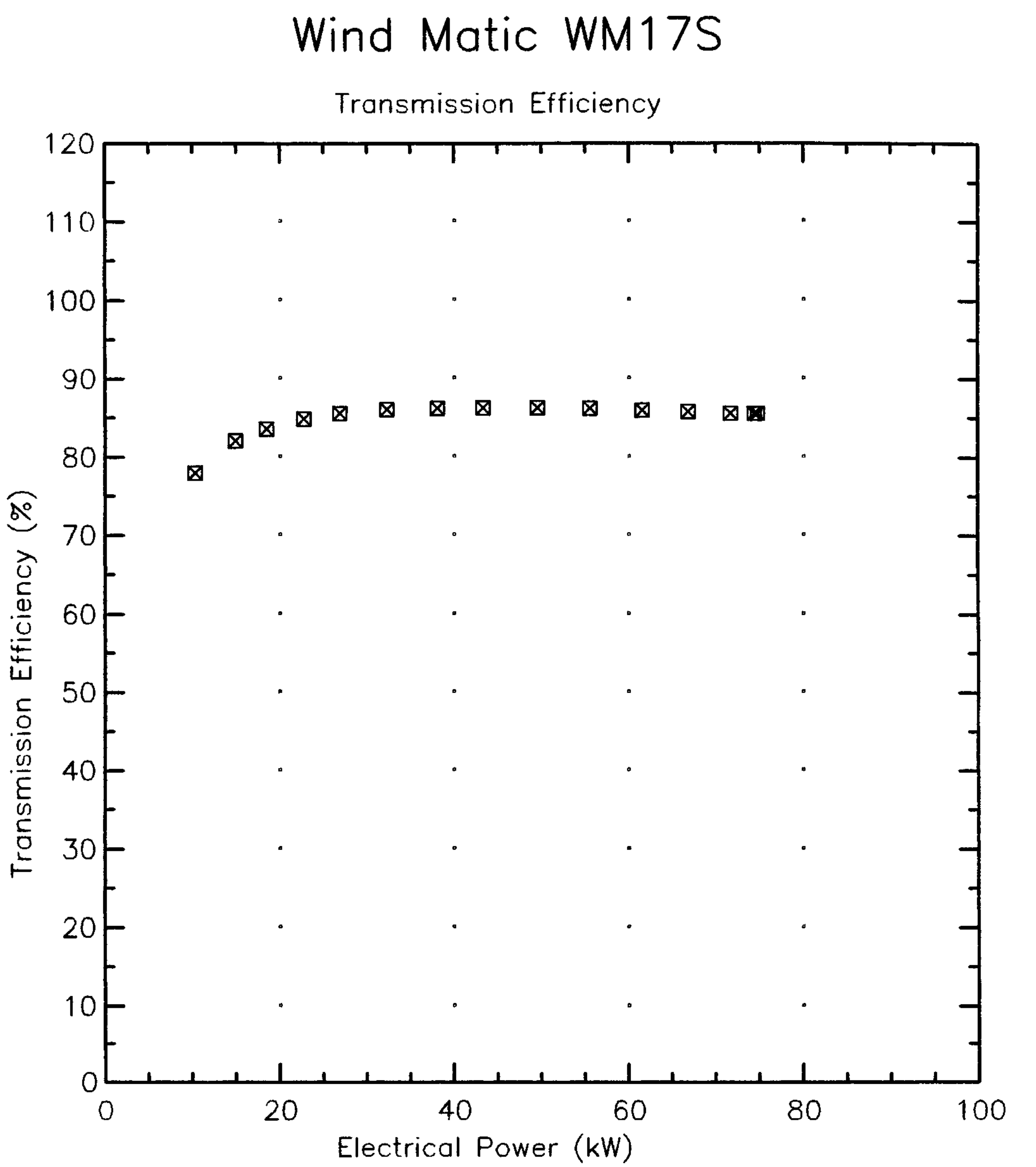
Immediately afterwards, the large generator was coupled to the grid. The absorbed power was now 5.7 kW, and after a total of six and a half hours operation on both generators the power dropped to 4.0 kW for an oil temperature of 56 deg(C).

The transmission efficiency of the turbine in operation was measured as described in chapter 3.2. The bin parameter was the wind speed. Measurements were performed from 9/9-85 to 11/9-85, totalling 70 hours of measurement time. The result is shown in Fig. 5.3.1 and in Table 5.3.2.

The maximum transmission efficiency is 86.3 % at about 45 kW electric power, and below 25 kW the efficiency drops off. In the region up to about 10 kW the turbine operates on the small generator, but data in this region are not available.

5.4 Rotor Performance.

The power delivered from the rotor shaft to the nacelle is a measure of the ability of the wind turbine blades to extract energy from the wind.



Data origin: Measurement
Measurement period 9-Sep-85 to 11-Sep-85
Total measurement time: 70 Hours

TURBINE DATA

Rotor diameter 16.99 m
Swept area 226.7 m**2
Rotational speed 39 rpm and 55 rpm
Tip angle: 1.4, 1.1 and 1.3 deg

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Fig. 5.3.1 Transmission efficiency.

Table 5.3.2 Tabulated data for transmission efficiency.

Wind Matic WM17S RISO-M-2546

ROTOR DIAMETER (M): 16.99 m
SWEPT AREA (M**2): 226.7 m**2
ROTATIONAL SPEED (RPM): 39 rpm and 55 rpm
TIPANGLE (DEG): 1.4, 1.1 and 1.3 deg
MEASUREMENT PERIOD: 9-Sep-85 to 11-Sep-85
MEASUREMENT TIME: 70 Hours

MEASURED DATA CURVE: Transmission Efficiency

X: Electrical Power (kW)
Y: Transmission Efficiency (%)

	X	Y
1	10.34	78.000
2	14.92	82.100
3	18.47	83.600
4	22.80	84.900
5	26.90	85.600
6	32.33	86.100
7	38.12	86.200
8	43.37	86.300
9	49.56	86.300
10	55.56	86.200
11	61.56	86.000
12	66.83	85.800
13	71.71	85.600
14	74.46	85.600
15	74.76	85.600

The rotor shaft power is calculated from the measurements of the power curve and the transmission efficiency. A linear interpolation is used for the transmission efficiency. The mechanical power curve is shown in fig. 5.4.1. and the data are tabulated in table 5.4.2. The corresponding rotor efficiency is shown in fig. 5.4.3 and the data tabulated in table 5.4.4.

The maximum efficiency is 52 % at 7 m/s. This point might lie very close to point where one generator shifts to the other; therefore the data might have some inaccuracy. The maximum power output is 86 kW at a wind speed of 12.5 m/s.

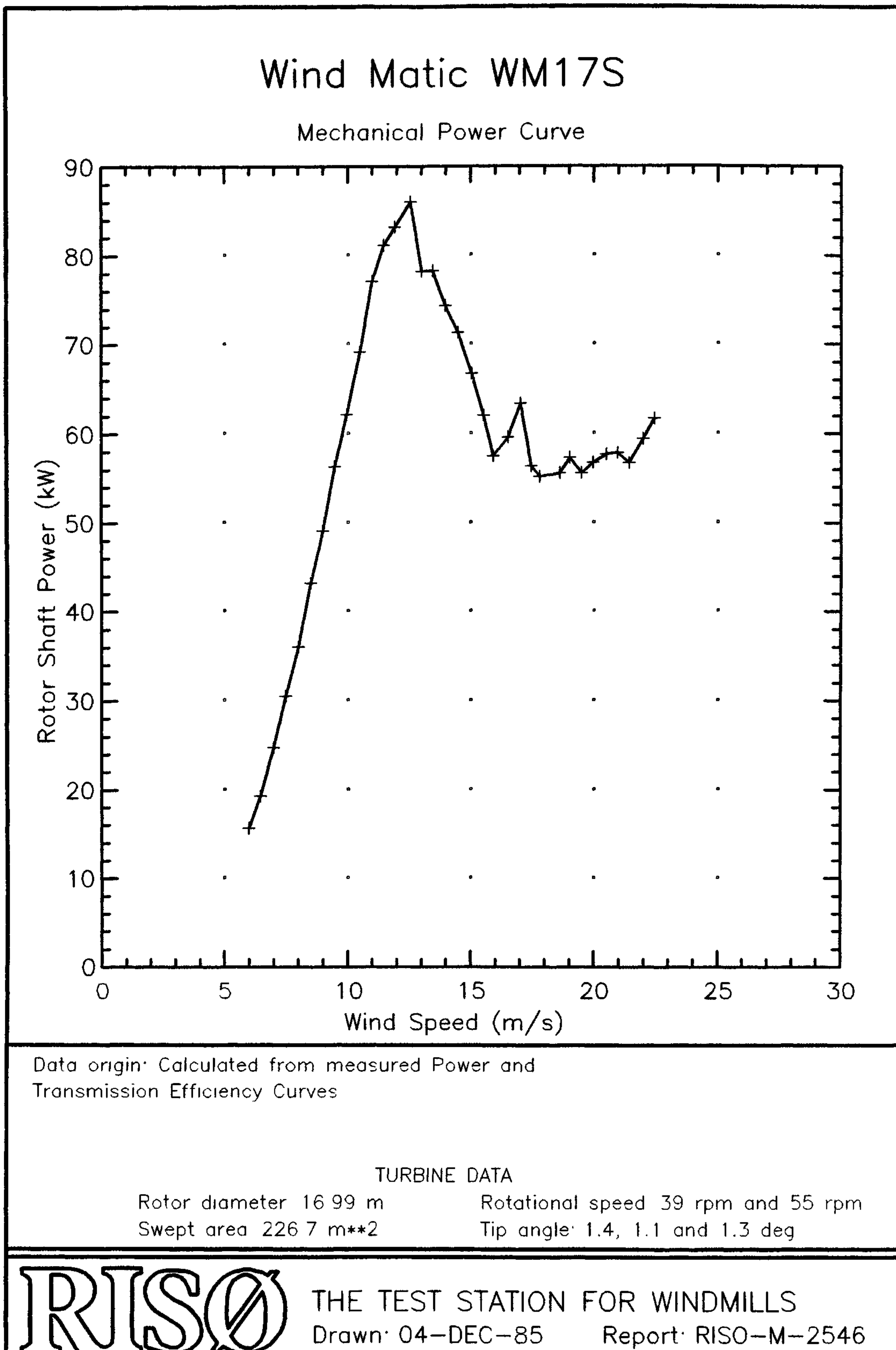


Fig. 5.4.1 Mechanical power curve.

Table 5.4.2 Tabulated data for mechanical power curve.

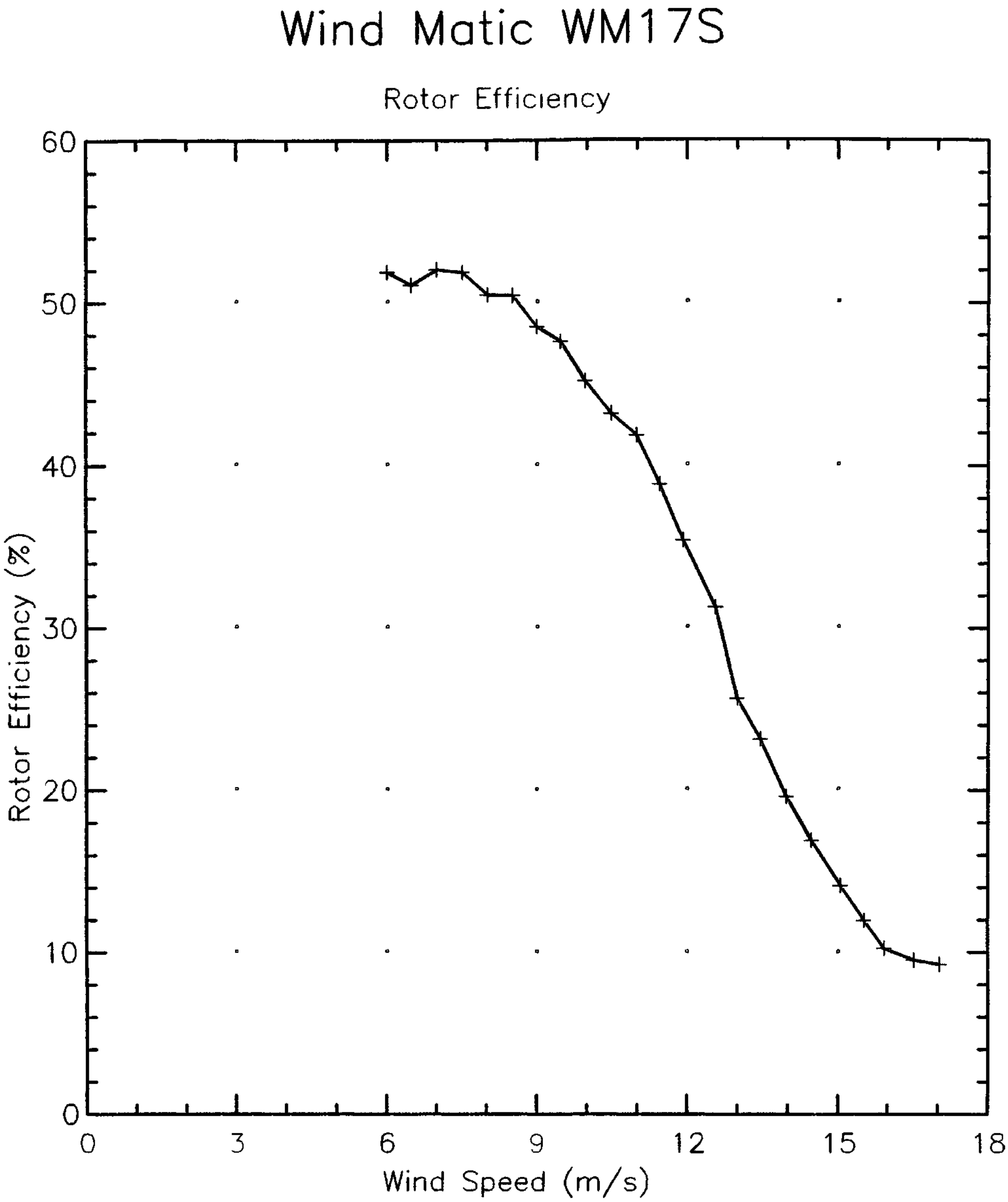
Wind Matic WM17S RISO-M-2546

ROTOR DIAMETER (M): 16.99 m
SWEPT AREA (M**2): 226.7 m**2
ROTATIONAL SPEED (RPM): 39 rpm and 55 rpm
TIPANGLE (DEG): 1.4, 1.1 and 1.3 deg
MEASUREMENT PERIOD: Calculated
MEASUREMENT TIME: None

MEASURED DATA CURVE: Mechanical Power Curve

X: Wind Speed (m/s)
Y: Rotor Shaft Power (kW)

	X	Y
1	6.01	15.640
2	6.48	19.300
3	7.00	24.790
4	7.51	30.510
5	8.01	36.030
6	8.51	43.170
7	9.00	49.110
8	9.48	56.320
9	9.97	62.130
10	10.49	69.170
11	10.99	77.120
12	11.46	81.150
13	11.92	83.210
14	12.56	86.060
15	13.00	78.230
16	13.46	78.280
17	13.98	74.380
18	14.48	71.380
19	15.05	66.760
20	15.53	62.110
21	15.93	57.510
22	16.52	59.670
23	17.03	63.420
24	17.46	56.410
25	17.81	55.210
26	18.63	55.600
27	19.02	57.380
28	19.51	55.640
29	19.98	56.830
30	20.50	57.720
31	20.95	57.900
32	21.43	56.780
33	21.98	59.430
34	22.46	61.770



Data origin: Calculated from Mechanical Power Curve

TURBINE DATA

Rotor diameter 16.99 m — Rotational speed 39 rpm and 55 rpm

Swept area 226.7 m**2 — Tip angle 1.4, 1.1 and 1.3 deg

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Fig. 5.4.3 Rotor efficiency

Table 5.4.4 Tabulated data for rotor efficiency.

Wind Matic WM17S RISO-M-2546

ROTOR DIAMETER (M): 16.99 m
SWEPT AREA (M**2): 226.7 m**2
ROTATIONAL SPEED (RPM): 39 rpm and 55 rpm
TIPANGLE (DEG): 1.4, 1.1 and 1.3 deg
MEASUREMENT PERIOD: Calculated from mea. data
MEASUREMENT TIME: None

MEASURED DATA CURVE: Rotor Efficiency

X: Wind Speed (m/s)
Y: Rotor Efficiency (%)

	X	Y
1	6.01	51.890
2	6.48	51.080
3	7.00	52.050
4	7.51	51.880
5	8.01	50.490
6	8.51	50.450
7	9.00	48.510
8	9.48	47.600
9	9.97	45.140
10	10.49	43.150
11	10.99	41.840
12	11.46	38.830
13	11.92	35.380
14	12.56	31.280
15	13.00	25.640
16	13.46	23.110
17	13.98	19.600
18	14.48	16.930
19	15.05	14.100
20	15.53	11.940
21	15.93	10.240
22	16.52	9.530
23	17.03	9.240

5.5 Power quality.

The power quality is described through time tracks, frequency spectra and cut-in measurements. The time tracks in fig. 5.5.1 show that when the turbine operates on the large generator power peaks up to 88 kW are reached. The largest power gradient seem to be 56 kW in 5 sec. The time track was recorded at a wind speed just below the stalled condition. This area must be expected to contain the largest power fluctuations.

The frequency spectra in fig. 6.1.4 shows a pronounced frequency content at 0.88 Hz, which is the rotor rotational frequency, and around 3 times this frequency. Above 3 Hz the frequency content is negligible.

Concerning grid loads in the cut-in sequence chapter 6.2 describes the grid current.

5.6 Rotor torque at standstill.

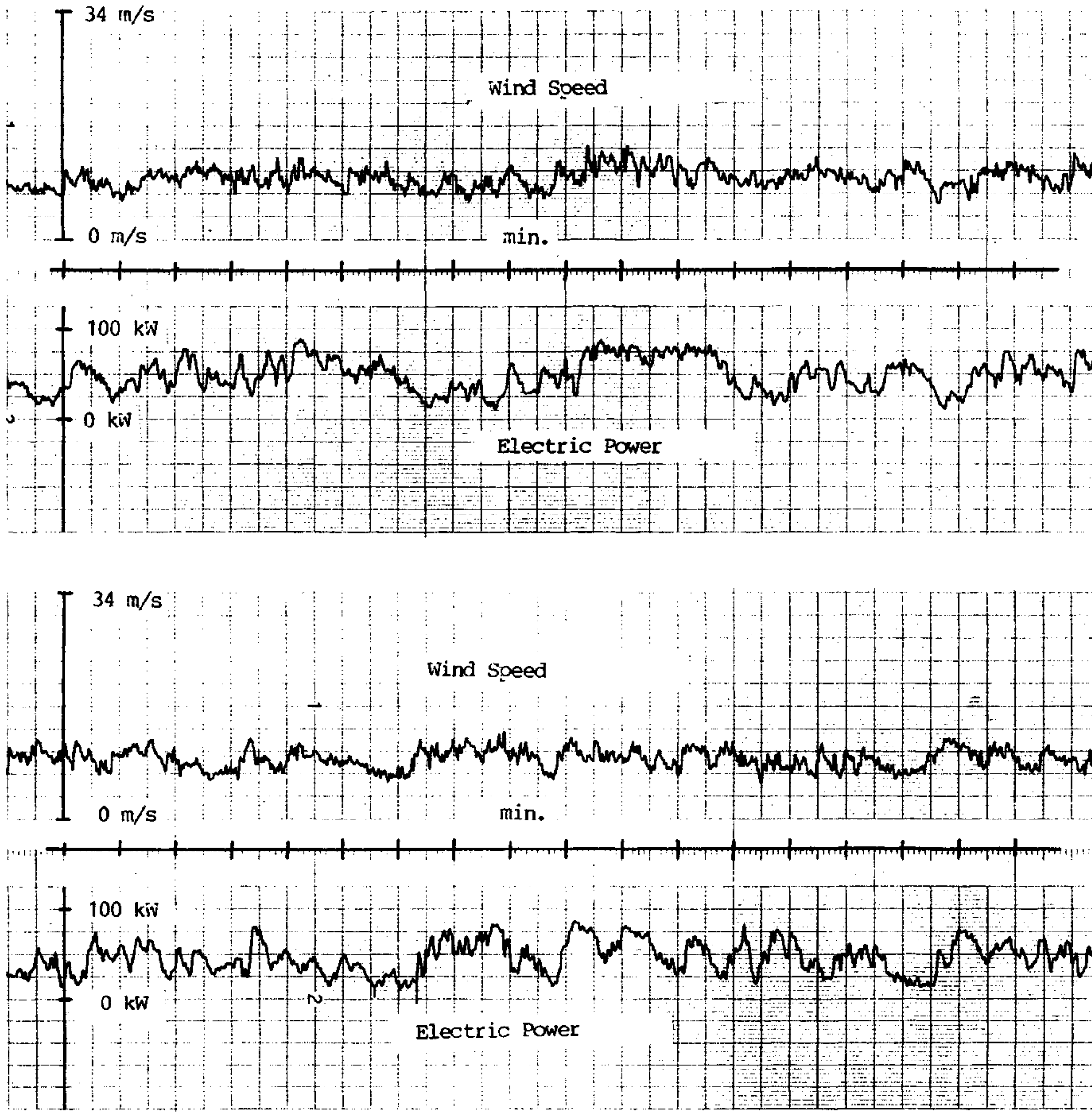
The start up conditions for the turbine are important because a lot of energy can be lost at the lower wind speeds if no special care has been taken to this point.

Figure 5.6.1 shows the measured rotor torque at standstill. It was measured at high wind speeds, but the curve can be extrapolated because it fits a second-order polynomial. The corresponding data are given in table 5.6.2.

The turbine had no problems with the start-up conditions. Electric motoring on the small generator was employed in the control system for situations where the rotor not did start by itself. An anemometer monitored these conditions, and the system worked very well.

Wind Matic WM17S

Electric Power



TURBINE DATA

Rotor diameter: 16.99 m
Swept area: 226.7 m**2
Rotational speed: 39 rpm and 55 rpm
Tip angle: 1.4, 1.1 and 1.3 deg

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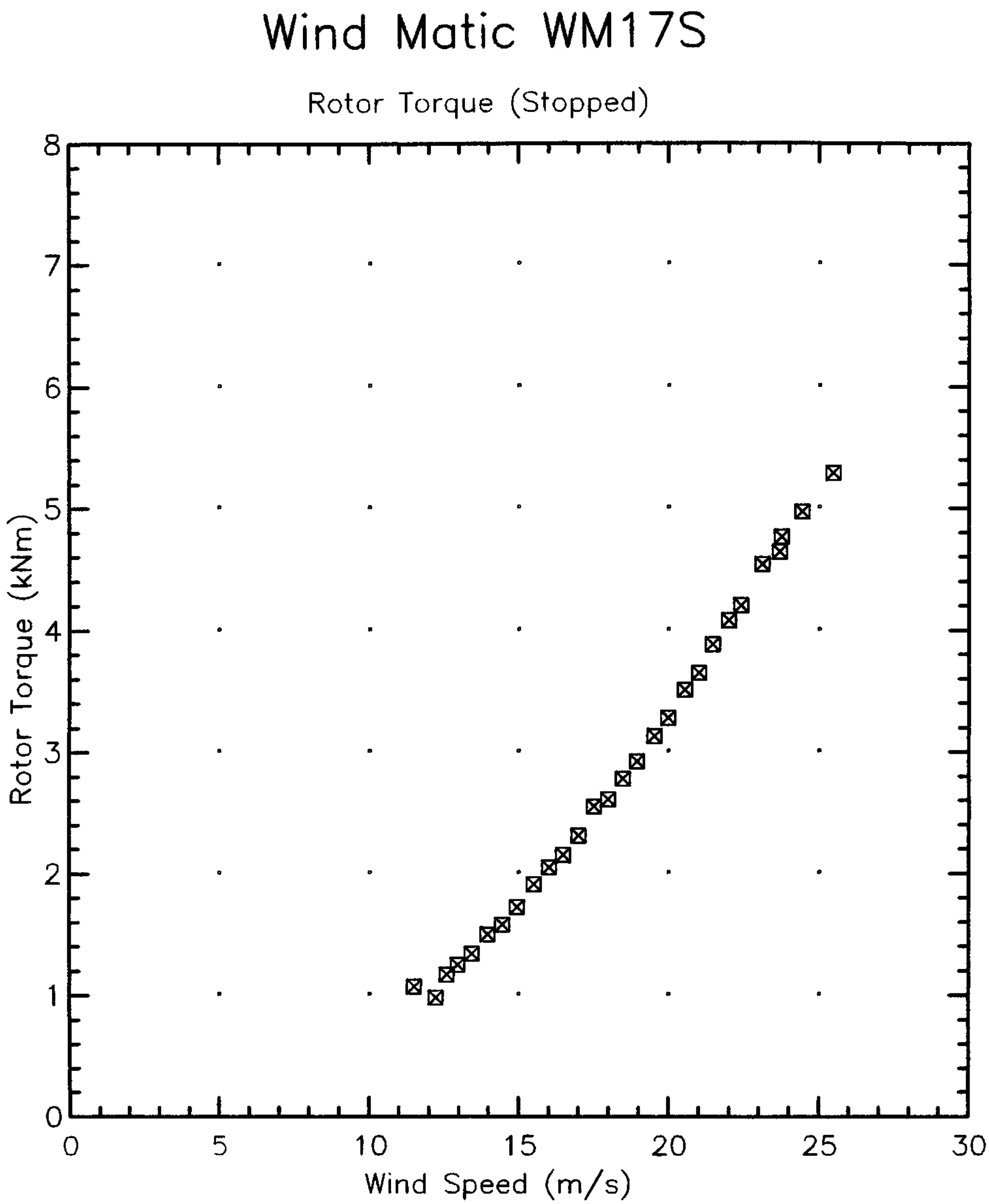
Fig. 5.5.1 Power fluctuations.



Data origin: Measurement
Measurement period 5-Sep-85
Total measurement time: 16 Hours

TURBINE DATA

Rotor diameter 16.99 m
Swept area 226.7 m**2
Rotational speed 39 rpm and 55 rpm
Tip angle 1.4, 1.1 and 1.3 deg

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Drawn: 04-DEC-85 Report: RISO-M-2546

Fig. 5.6.1 Rotor torque of standstill.

Table 5.6.2 Data for rotor torque at standstill.

Wind Matic WM17S RISO-M-2546

ROTOR DIAMETER (M): 16.99 m
SWEPT AREA (M**2): 226.7 m**2
ROTATIONAL SPEED (RPM): 39 rpm and 55 rpm
TIPANGLE (DEG): 1.4, 1.1 and 1.3 deg
MEASUREMENT PERIOD: 5-Sep-85
MEASUREMENT TIME: 16 Hours

MEASURED DATA CURVE: Rotor Torque (Stopped)

X: Wind Speed (m/s)
Y: Rotor Torque (kNm)

	X	Y
1	11.51	1.073
2	12.23	0.980
3	12.59	1.174
4	12.97	1.249
5	13.44	1.338
6	13.98	1.499
7	14.47	1.576
8	14.96	1.722
9	15.51	1.909
10	16.02	2.046
11	16.50	2.151
12	17.01	2.309
13	17.53	2.547
14	18.00	2.613
15	18.50	2.782
16	18.96	2.917
17	19.54	3.132
18	19.99	3.281
19	20.54	3.506
20	21.02	3.650
21	21.47	3.881
22	22.01	4.081
23	22.41	4.201
24	23.12	4.541
25	23.70	4.641
26	23.76	4.764
27	24.44	4.968
28	25.47	5.292

6. STRUCTURAL MEASUREMENTS.

Structural measurements deal with measurements of vibrations in the construction with very few sensors, and loads at cut-in.

6.1 Structural dynamics

The vibrations in the construction were measured with strain-gauge bridges mounted for the edgewise and flapwise root bending moments in one blade and the rotor torque on the main shaft.

Frequency spectra were measured for the following conditions.

1. The wind turbine was stopped with the rotor towards the free wind. The blade was set in four positions; vertical upwards, horizontal with the leading edge downwards, vertical downwards and horizontal with the trailing edge downwards.

2. The wind turbine operating on the large generator.

The measurements according to point 1 are used for determining eigenfrequencies in the structure. All vibrations originating from the rotation can be eliminated while the turbulence in the air is the only excitating force on the structure. These measurements indicate a tower bending mode frequency of 1.60 Hz, a torsional tower mode frequency of 2.04 Hz and a flapwise asymmetric rotor mode frequency of 2.32 Hz. The flapwise symmetric rotor mode frequency is 2.56 Hz.

Figure 6.1.1 shows the flapwise and edgewise bending moment at the blade root when the turbine operates on the large generator at a wind speed of approximately 8 m/s. Figure 6.1.2 shows the same but with the amplitudes enlarged ten times for analysis of the frequency content.

It is clearly seen that the dominant frequency both flapwise and edgewise is the rotational frequency of 0.90 Hz. The frequencies 1.80 Hz and 2.69 Hz are 2 p and 3 p respectively. Higher harmonics can be seen at higher frequencies up to 10 Hz. The frequency 9.84 Hz is 11 p. A frequency of about 2.80 Hz is seen to be dominant over the 3 p frequency at 2.69 Hz and the flapwise symmetric rotor mode frequency at 2.56 Hz. It is remarkable here that the frequency response around the 3 p frequency seems to be very well damped although the flapwise symmetric rotor mode, i.e. the blade eigenfrequency, is very close to the excitational frequency due to tower shadow. 2 p is seen to have just as high a vibrational energy content.

Generally speaking, the frequency spectra show a well damped blade where the dominant vibrational content lies in the rotational frequency. A high degree of coupling between the flapwise and edgewise bending moments is seen and this makes it more difficult to distinguish among the different vibration modes.

Time traces for the two bending moments are shown in fig. 6.1.3.

Frequency spectra for the rotor torque and electric power are shown in fig. 6.1.4. Due to very good correlation between the two parameters the spectra are almost alike. 1 p is dominant in amplitude, but more energy is dissipated through the 3 p frequency 2.69 Hz together with the vibration mode at 2.80 Hz, which was also found in the blade bending moments. Above 3 Hz the vibrations die out.

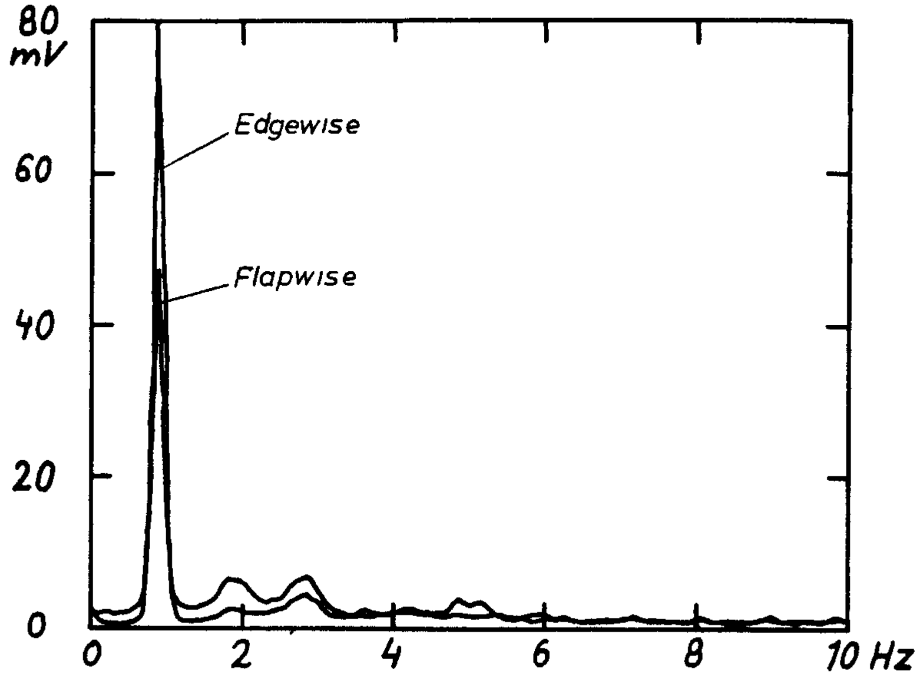


Fig. 6.1.1. Frequency spectra of flapwise and edgewise blade root bending moments when operating on large generator.

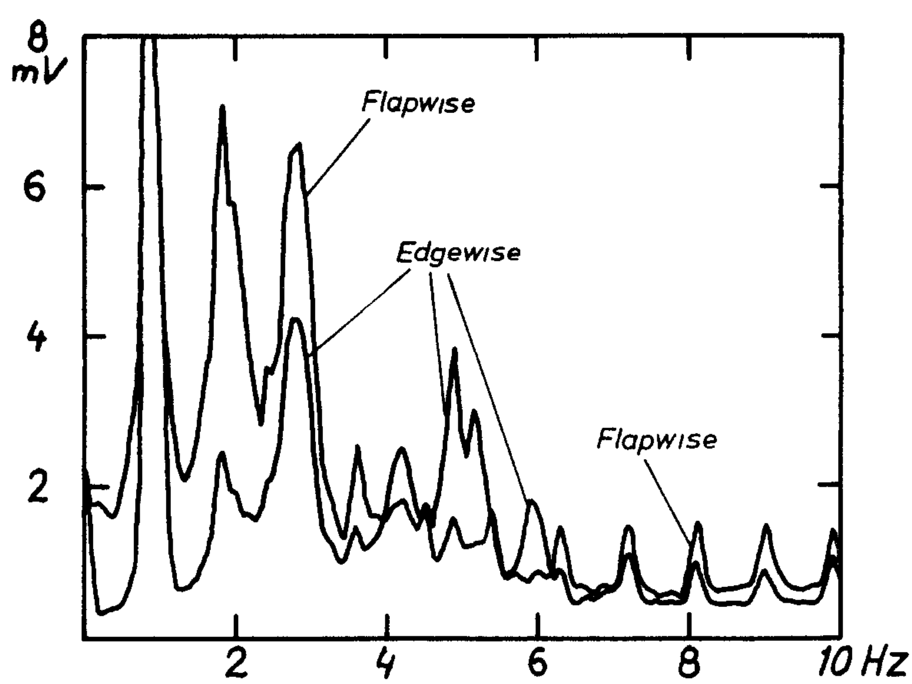


Fig. 6.1.2 Frequency spectra of flapwise and edgewise blade root bending moments (enlarged).

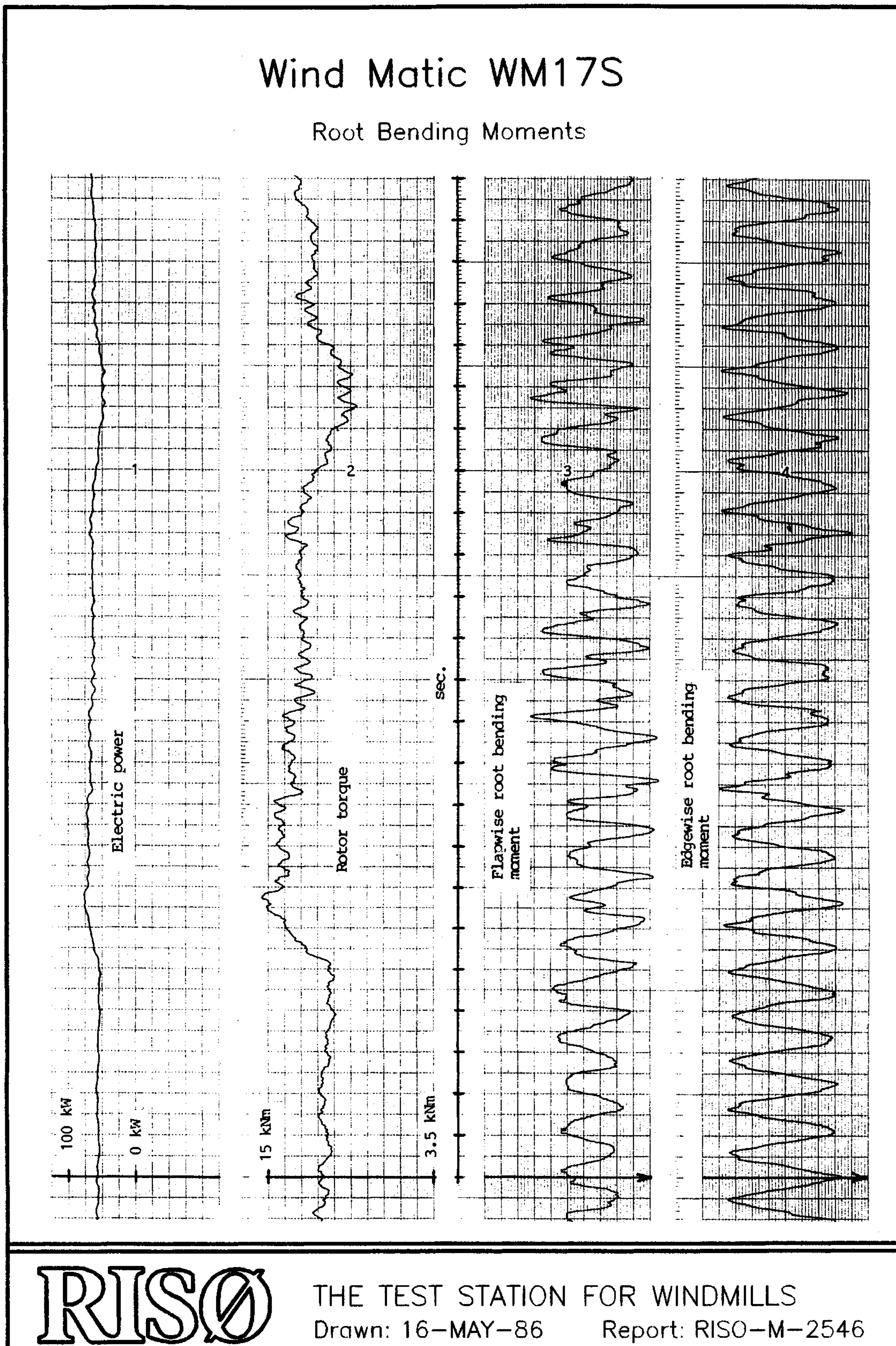


Fig. 6.1.3 Time traces of the blade root bending moments.

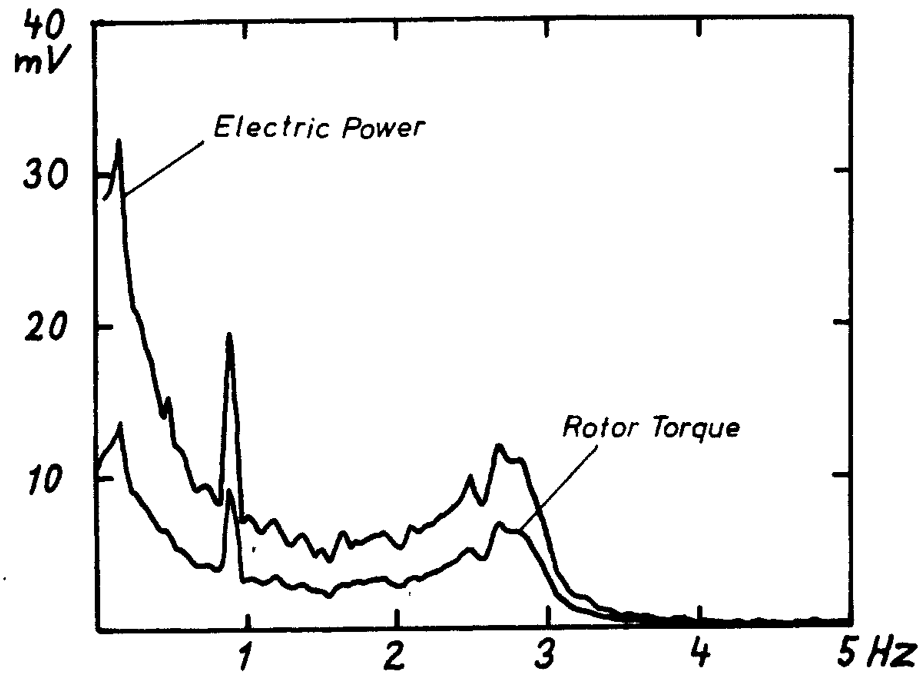


Fig. 6.1.4 Frequency spectra of rotor torque and electric power.

6.2 Loads at cut-in.

A cut-in sequence on the large generator at about 50% power is shown in fig. 6.1.1. The signals for rotor shaft torque and electrical current on one phase are unfiltered while the electrical power and generator rotational speed are filtered with a 20-Hz low pass filter. The absolute figures for the rotational speed are not necessarily correct. Their level is estimated from the power on the generator after cut-in.

The rotor shaft torque raises to a maximum of 14.1 kNm during cut-in and the curve is very soft. This torque corresponds to 94% of that at full power with 86 kW delivered from the rotor. The torque might be less when cut-in is performed at normal power.

The electrical current has a maximum of 313 Amp in amplitude. This current corresponds to 156% of the current at full power with 73.7 kW delivered from the generator when the calculation of the effective current is presuming a sinusoidal curve during the cut-in sequence, and a cos of 0.79.

The maximum cut-in current is relatively large, because it is an abnormal cut-in condition at 50% power. Smaller values must be expected at normal cut-in at about 25% power.

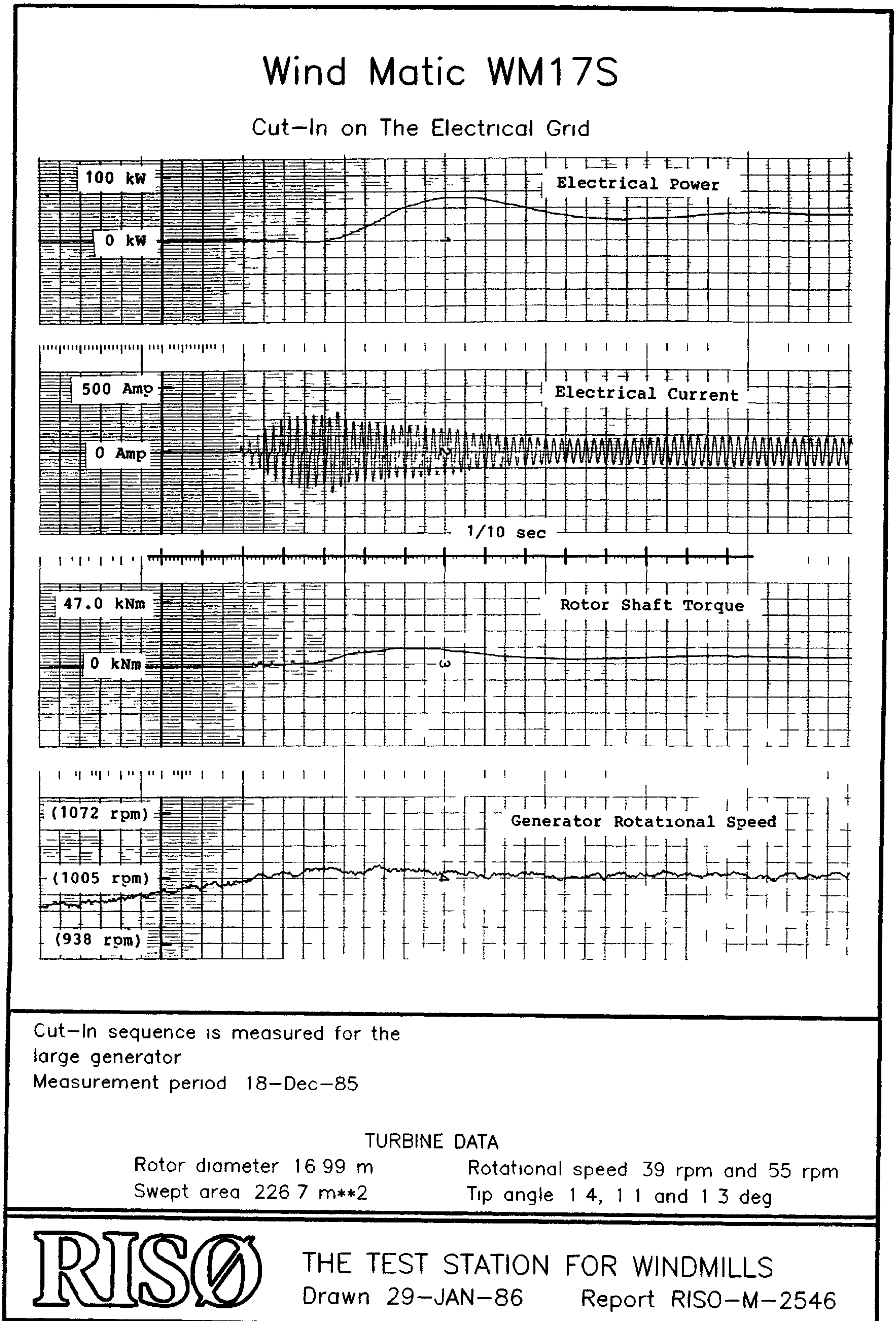


Fig. 6.1.1 Loads at cut-in.

7. ENVIRONMENTAL MEASUREMENTS

The wind turbine has a certain environmental impact, and the most important part of this is noise emission.

7.1 Noise emission.

The noise emission was measured by a subcontractor, and the result is reported in Appendix A.

The A-weighted sound pressure level was measured 1.4 m above the ground 20 and 40 behind the wind turbine and also 20 m to the right of the rotor plane when facing the wind. The wind speed was registered in 10 m height.

The main result is shown in fig. 7.1. The measurement point is 20 m behind the windmill, 1.4 m above the ground. When operating on the small generator the sound pressure level is about 50 dB (A). On the large generator the sound pressure level is raised to about 56 dB (A) at 6 m/s, increasing by 2 dB (A) at 9 m/s.

According to the narrow band spectra a clear tone at 1305 Hz could indicate an addition of 5 dB (A) to the measured A-weigted sound pressure level according to the official Danish Regulations, but at a distance of 40 m from the windmill the clear tone has not been traced.

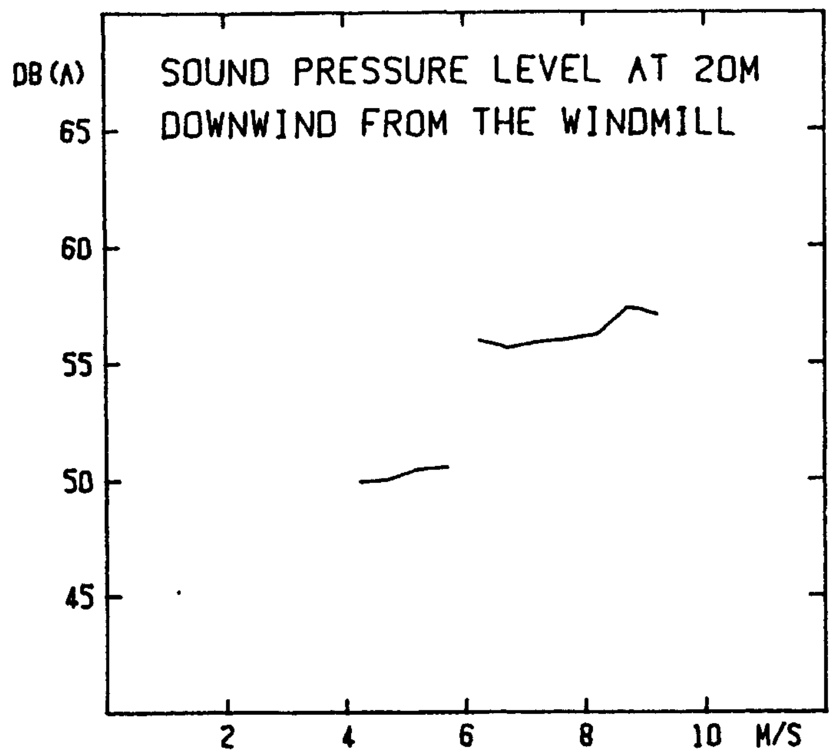


Fig. 7.1 The energy equivalent A-weighted sound pressure level 20 m downwind.

SUMMARY

The standard test comprised tests of the safety systems: mechanical and air brakes. The mechanical brake was tested at 85% power by disconnecting the main switch and the rotor was stopped after a safe brake sequence. The brake torque was almost constant at 210% the maximum operational rotor torque and the cut-in of the brake was well damped, eliminating high transient loads. The efficiency of the air brakes was measured for a free running rotor and the normal rotational speed of 55 rpm was reached at 14 m/s. At higher wind speeds the rotational speed is expected to rise proportional. At 30 m/s the rotational speed is expected to be 132 rpm, which is very high.

The performance measurements show a maximum overall efficiency of 44.3% at 7.5 m/s and a maximum power of 73.7 kW at 12.5 m/s. The power regulation by stall is efficiently lowering power at higher wind speeds. The calculated energy production shows 110, 168 and 222 MWh for Rayleigh distributed wind speeds with annual mean wind speeds of 5, 6 and 7 m/s. The corresponding annual energy productions per square meter are 485, 741 and 979 kWh/m^2.

The maximum transmission efficiency is 86.3 % at about 45 kW and below 25 kW the efficiency drops of. The maximum rotor efficiency is 52% at 7 m/s, which must be considered to be quite high. Power fluctuations were relatively high, showing power increase of 11 kW/sec during 5 seconds. The rotor had no starting problems due to an efficient and reliable start up mechanism.

The construction is generally well damped and no eigenfrequencies seem to be periodically excitated to give dangerous unstable structural dynamics. The blade eigenfrequency lies close to the blade/tower excitating frequency, but apparently the blades do not suffer from this.

The torque at cut-in lies below the nominal operational torque. The max. transient current however, is about 50% more than that at full power, but the measurement was carried out at an unnormal cut-in condition at 50% nominal power.

The noise level was found as about 58 dB (A) at 9 m/s at a distance of 20 m from the windmill.

REFERENCES

1. "Guidance for Test of Wind Turbines" (Danish). Troels Friis Pedersen, September 1985

2. "Recommended Practices for Wind Turbine Testing and Evaluation. 1 Power Performance Testing". IEA 1982.

3. "WM 17S Manual, type 0. September 1985

4. "Standard measurements on windmills at The Test Station for Windmills at Risø, Denmark"
   Troels Friis Pedersen, 1983.

5. "Wind Atlas for Denmark"
   Erik Lundtang Petersen, Ib Troen, Steen Frandsen, 1980.

ENERGI-OG MILJØ
dk TEKNIK
DANSK KEDELFORENING
GLADSAXE MØLLEVEJ 15 · 2860 SØBORG · (01) 69 65 11

APPENDIX A

R E P O R T

Risø National Laboratory
The Test Station for Windmills
Roskilde, Denmark
Windmatic 17S

Journal no.	73.85.518
Requisition no.	Risø M-2546
Test made	7-13/5 1985
Report made by	Peter Just/
	Poul Behnk

P. Just

Søborg, April 9th 1986
dk-TEKNIK

Noise Measurements

Type of Windmill:	Windmatic 17S
Location of Measurement:	The testing station for windmills, Risø
Period of Measurement:	7th-13th May 1985

1. Description of Measuring Locality

The windmill was placed upon a base, made specially for this purpose by the testing station.

The terrain around the windmill was approximately flat, falling from east towards west. At the fields around the windmill there was in the downwind direction a newly harrowed field, while the areas in the plane of rotation of the windmill were covered with short-cut grass.

In a distance of approx. 150 m from the windmill, the Frederikssund-Roskilde highway is situated, which accounts for a considerable traffic noise.

2. Description of Measurements

Registration was made of the A-weighted sound pressure level at 1.4 m above the ground at the following points:
P 1: 20 m from the windmill in the downwind direction.
P 2: 20 m from the windmill in the plane of rotation.
P 3: 40 m from the windmill in the downwind direction.

At P 1 there was also registration of sound level at 3.7 m above the ground. Furthermore the wind velocity at 10 m's height was registered.

3. Comments to the carried out Measurements and thereafter, if any, Subjective Evaluations

From figures 4, 5 and 6 it appears that the A-weighted sound pressure level, re. 20 μPa, in the downwind direction 20 m from the windmill with wind velocity measured at 10 m's height to be:

Date	7th/5	12th/5 -	13th/5
Height above ground	1.4 m	1.4 m	3.7 m
Wind Velocity			
10 m/s	58 dB(A)	-	-
5 m/s		50 dB(A)	51 dB(A)

The background sound level at a distance of 20 m from the windmill has been concluded to be 38-40 dB(A), re. 20 μPa, see figure 17 and 18, and thus corrections shall not be necessary. The background sound level on the 7th May at 40 m from the windmill, see figure 19, shows to be 50 dB(A), re. 20 μPa, which means that corrections shall not be necessary.

From the narrow band spectrum analysis it appears that the sound spectrum contains a number of weak clear tone components, which can hardly be supplemented with a + 5dB according to the official Danish Regulations.* Still the clear tone at 1305 Hz could have higher values in comparison to the sound level, see figure 9. At a bigger distance from the windmill, 40 m, that clear tone component at 1305 Hz has not been traced, according to figures 13 and 14.

* National Agency of Environmental Protection.
Guidelines Nos 6 and 6/1984: External Noise

Summary of Figures

Figure(s):

1. Instruments used.

Recordings of the A-weighted sound pressure level:

2. At 1.4 m above ground in downwind and plane of rotation respectively

3. At 1.4 m above ground in downwind and plane of rotation respectively

Sound pressure level as a function of wind velocity:

4 At downwind 1.4 m above ground on 7th May, 1985

5 At downwind 1.4 m above ground on 12th/13th May 1985

6 At downwind 3.7 m above ground

20 For the Nordic (nordiske) windmill catalogue Narrow

Band Spectrum analysis of the A-weighted sound pressure level:

7,8,9 20 m from the windmill in downwind direction, 1.4 m above ground

10,11,12 20 m from the windmill in plane of rotation, 1.4 m above ground

13,14 40 m from the windmill in downwind direction, 1.4 m above ground

15,16 20 m from the windmill in downwind direction, 3.7 m above ground

Narrow Band spectrum analysis of the A-weighted background sound level:

17 20 m from the windmill in plane of rotation, 1.4 m above ground. Time 00.36 midnight.

18 20 m from the windmill in plane of rotation, 1.4 m above ground. Time 00.52 midnight.

19 20 m from the windmill in downwind direction, 1.4 m above ground.

MEASUREMENT EQUIPMENT:

The following types of instruments were used for measurements and analyses 20 m from windmill:

- ½" free-field condenser microphone, Brüel & Kjær type 4165, with windscreen, Brüel & Kjær type UA 0237, and flexible extension rod. 2 set.

- Microphone preamplifier, Brüel & Kjær type 2619. 2 set.

- Noiselevel analyser and statistical processor, Brüel & Kjær type 4426, with built-in A-weighting filter. Time weighting: FAST. 2 set.

- Alphanumeric printer, Brüel & Kjær type 2312. Intervals of 2 minutes print. 2 set.

- Graphic level recorder, Brüel & Kjær type 2312. Writing speed 250mm/s. Paper speed 0,1 mm/s. 50 dB log potentiometer. 2 set.
  40 m from windmill.

- Tape recorder, Revox type A 700, tape speed 9,5 cm/s. Revox type 631 tape.

- Impulse precision sound level meter, Brüel & Kjær type 2209
  with: microphone, Brüel & Kjær type 4165
  windscreen, Brüel & Kjær type UA 0237
  flexible extension rod.
  frequency weighting: A
  time weighting: FAST

- Tape recorder: Nagra type IV SJ, tape speed 9,5 cm/s. Agfa type 369 prof tape.

Other instruments:

- Sound level calibrator, Brüel & Kjær type 4230. 94 dB/1000 Hz.

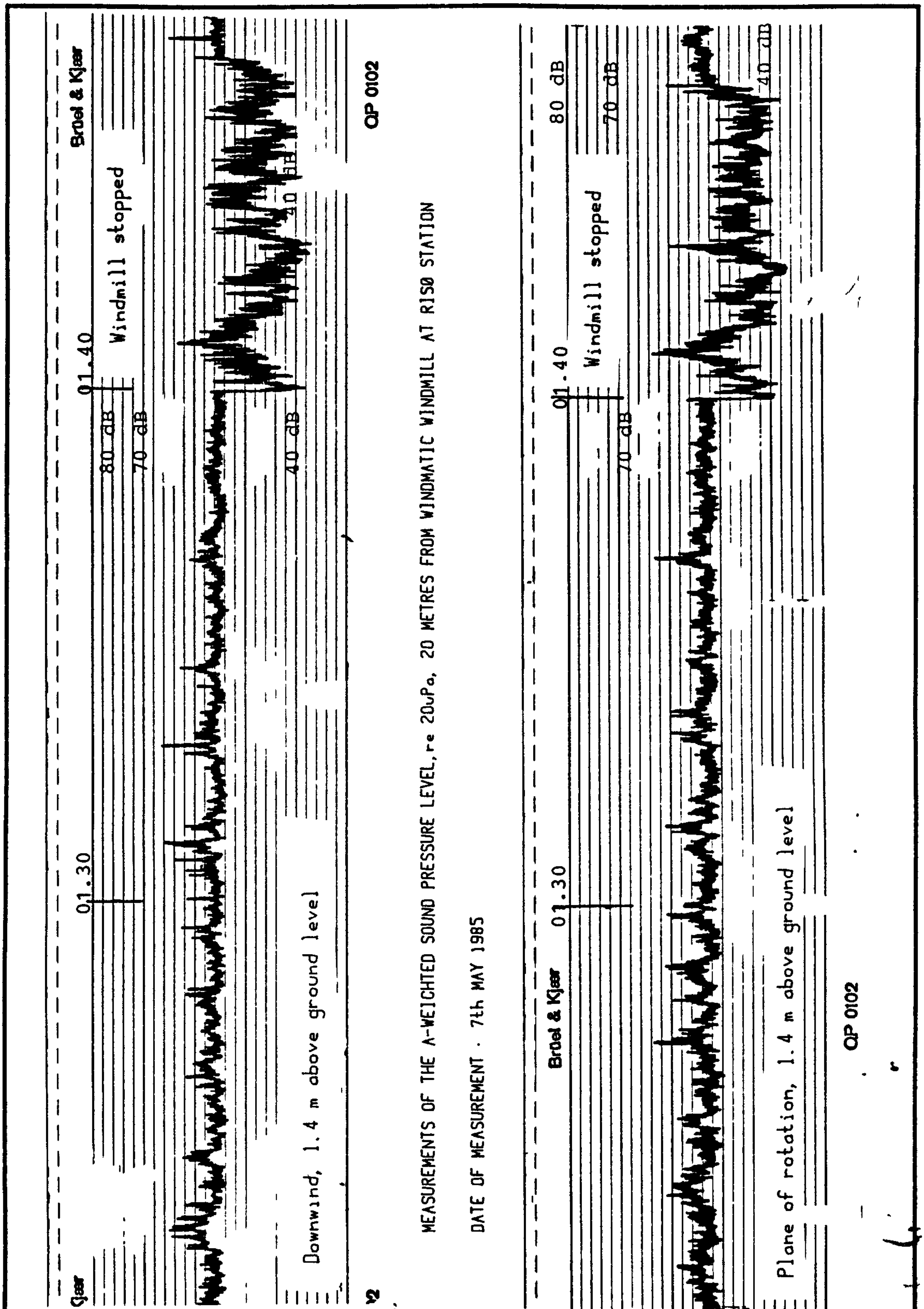
- Wind measurement system, windmaster type Mark III, 10 m over terrain.

- Winddatalogger, Hewlett Packard type 3421 A and 85.

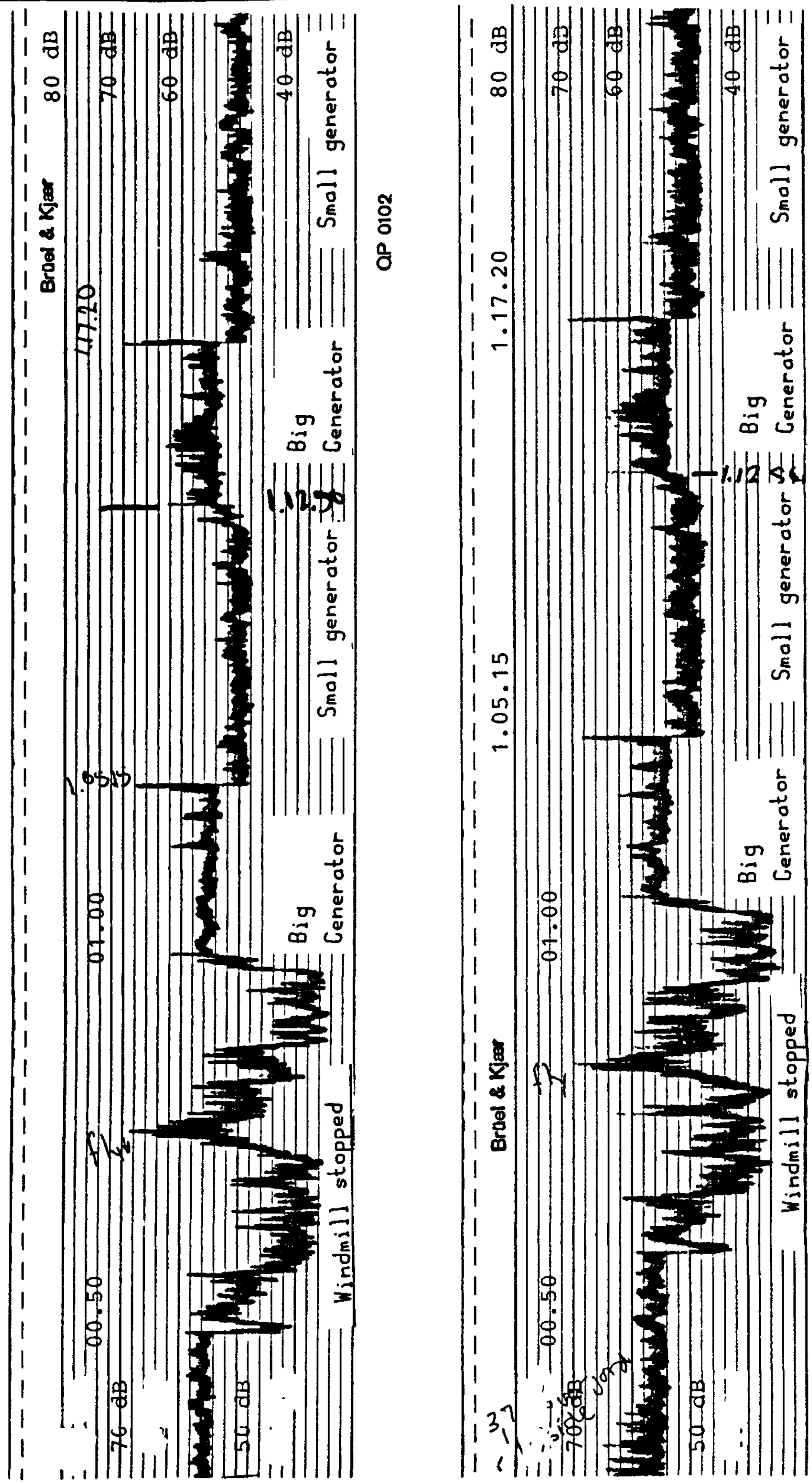
Analyse:

- Narrow band spectrum analyser, Brüel & Kjær type 2031. 400 frequency channels 0-2000 Hz, "Hanning" - weighting and "Linear"-averaging.

- Computer, Hewlett Packard type 86A with 7225 B and 9121.



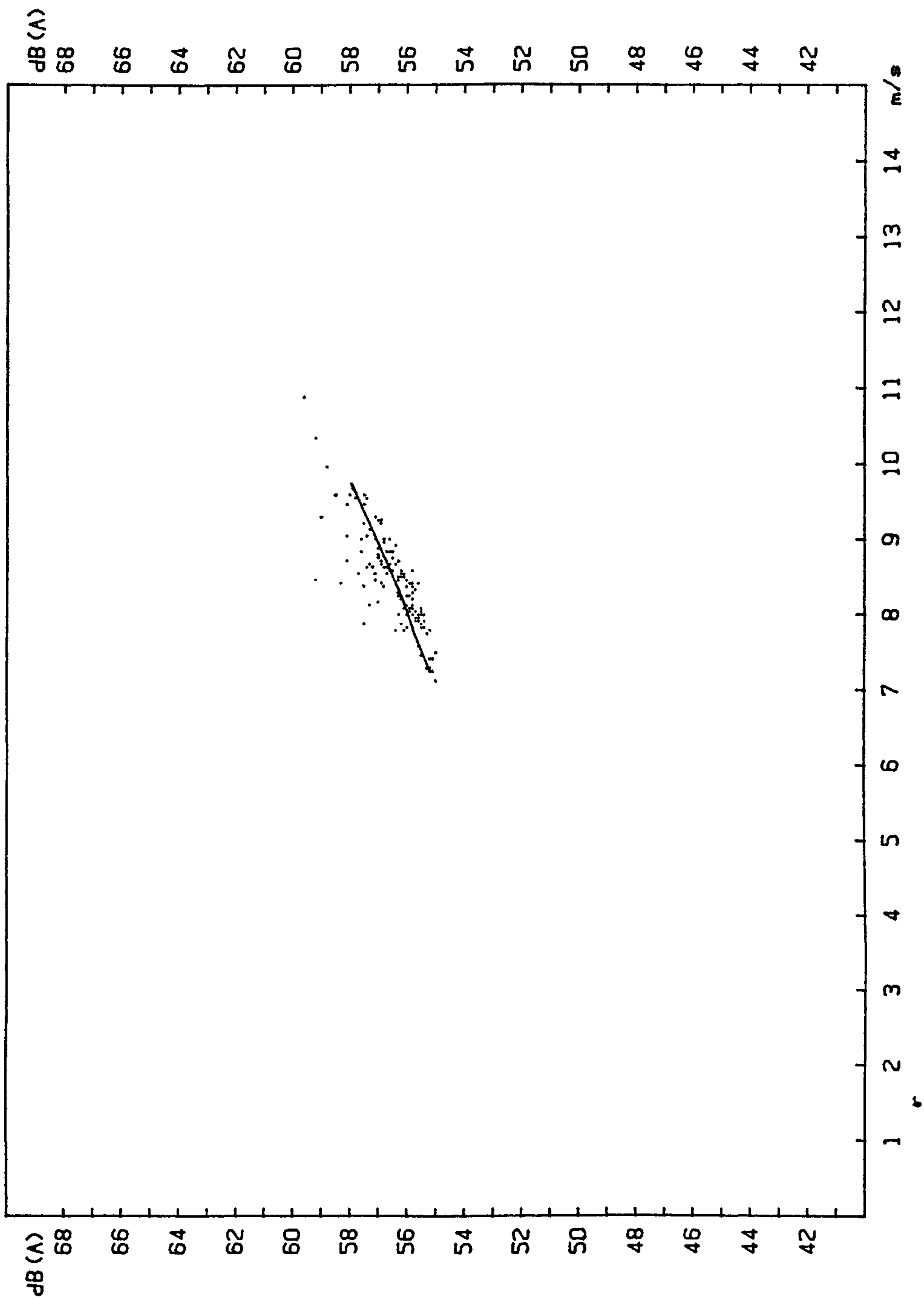
WINDMATIC 17S WINDMILL | RISØ | FIGURE 2



MEASUREMENTS OF THE A-WEIGHTED SOUND PRESSURE LEVEL, re 20uPa, 20 METRES DOWNWIND FROM WINDMATIC WINDMILL AT RISØ STATION

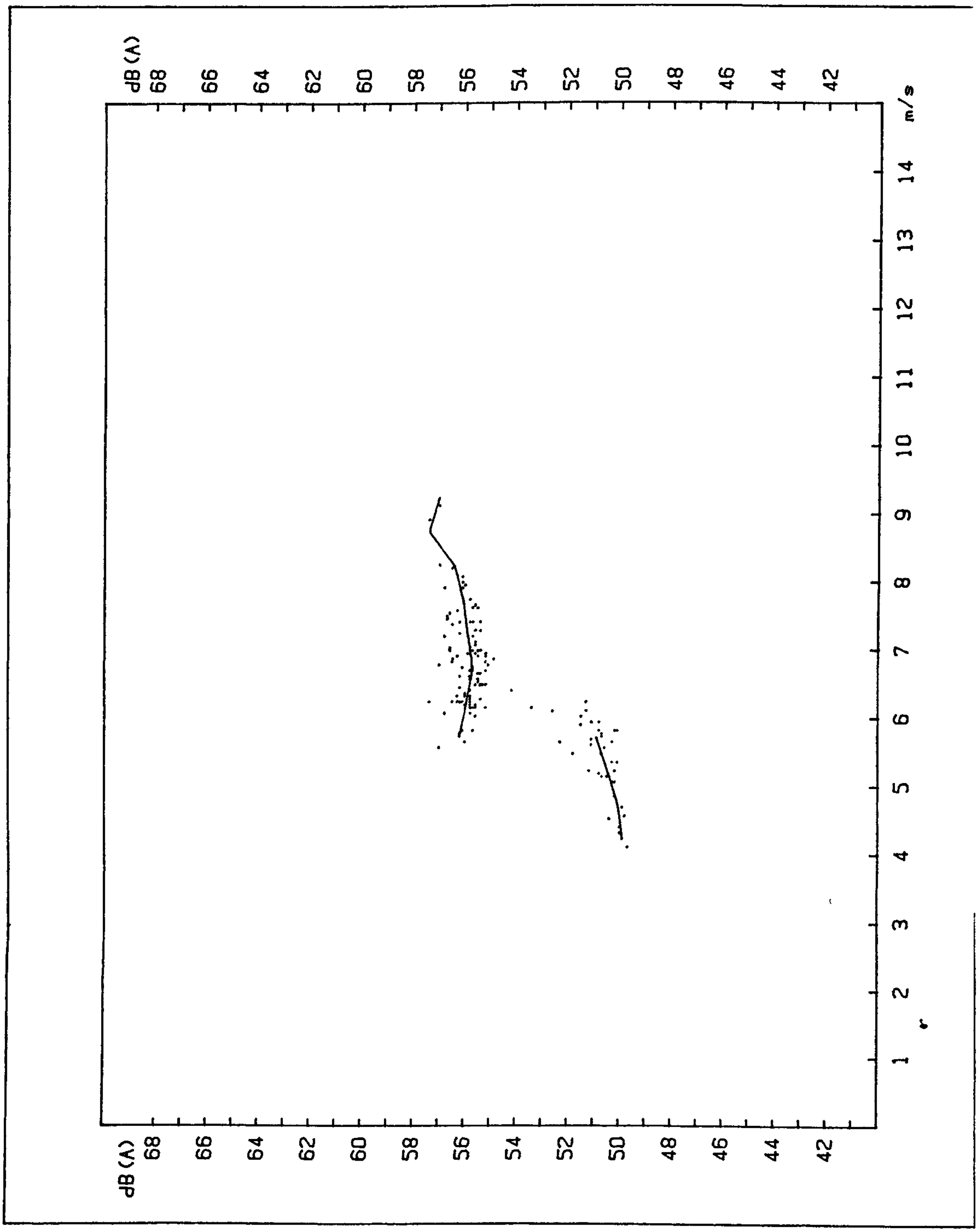
UPPER LEVEL RECORDINGS : 1.4 METRES ABOVE GROUND LEVEL.
LOWER LEVEL RECORDINGS : 3.7 METRES ABOVE GROUND LEVEL.
DATE OF MEASUREMENT : 12th / 13th MAY 1985

WINDMATIC 17S WINDMILL	RISØ	FIGURE 3



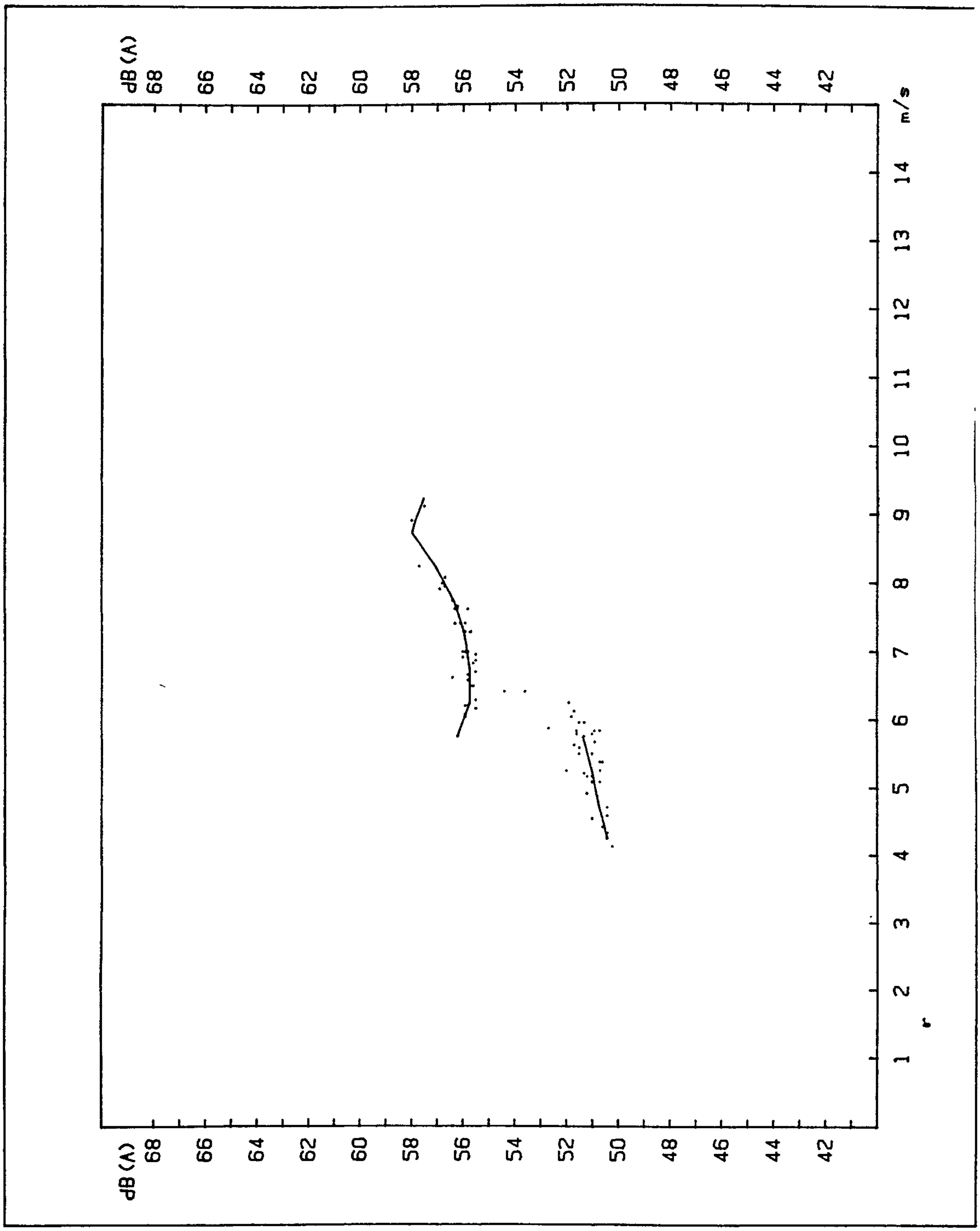
THE ENERGY EQUIVALENT A-WEIGHTED SOUND PRESSURE LEVEL FOR INTERVALS OF TWO MINUTES LENGTH VS. WIND VELOCITY 10 METRES ABOVE GROUND LEVEL.
MEASUREMENT POINT : 20 METRES DOWNWIND, 1.4 M ABOVE GROUND LEVEL.
DATE & TIME OF MEASUREMENT : 7th MAY 1985 00.00 - 06.00 am

WINDMATIC 17S WINDMILL	RISØ	FIGURE 4



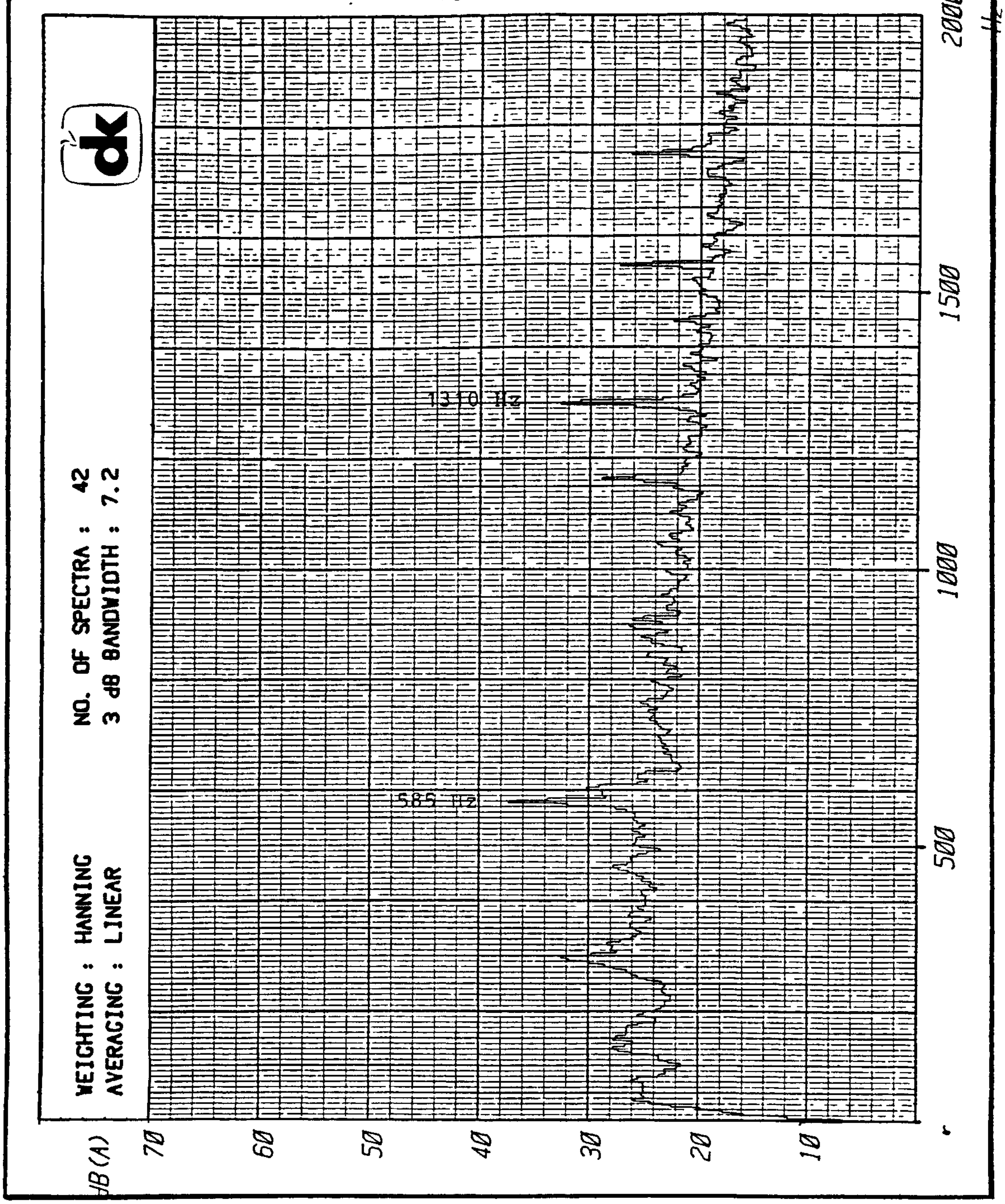
THE ENERGY EQUIVALENT A-WEIGHTED SOUND PRESSURE LEVEL FOR INTERVALS OF TWO MINUTES LENGTH VS. WIND VELOCITY 10 METRES ABOVE GROUND LEVEL.
MEASUREMENT POINT : 20 METRES DOWNWIND, 1.4 M ABOVE GROUND LEVEL.
DATE & TIME OF MEASUREMENT : 12th - 13th MAY 1985 22.30 - 06.00 am

WINDMATIC 17S WINDMILL	*RISØ*	*FIGURE 5*



THE ENERGY EQUIVALENT A-WEIGHTED SOUND PRESSURE LEVEL FOR INTERVALS OF TWO MINUTES LENGTH VS. WIND VELOCITY 10 METRES ABOVE GROUND LEVEL
MEASUREMENT POINT : 20 METRES DOWNWIND, 3.7 M ABOVE GROUND LEVEL.
DATE & TIME OF MEASUREMENT : 13th MAY 1985 01.00 - 04.24 am

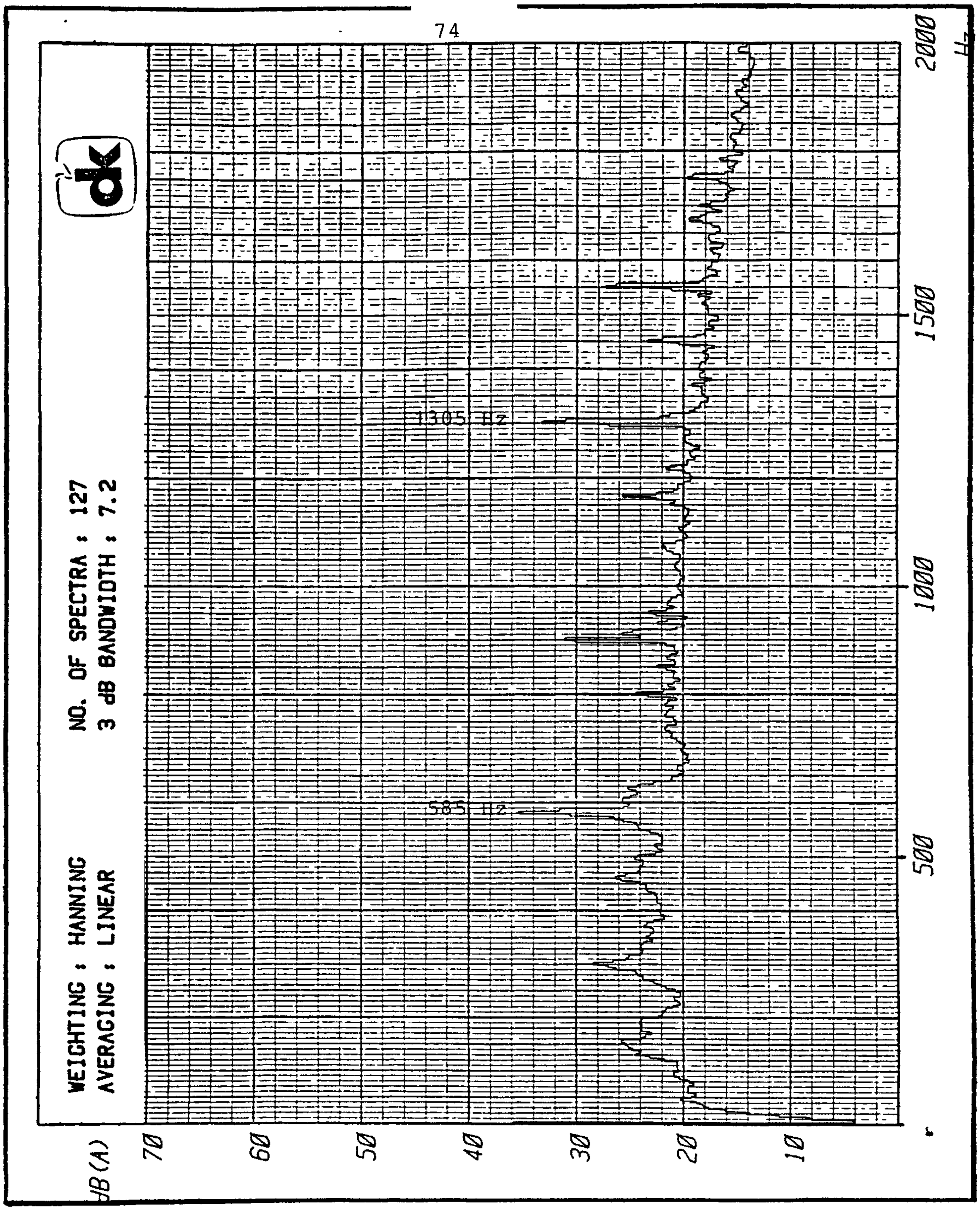
WINDMATIC 17S WINDMILL	RISØ	FIGURE 6



NARROW BAND SPECTRUM ANALYSIS OF THE A-WEIGHTED SOUND PRESSURE LEVEL

MEASUREMENT POINT : 20 METRES DOWNWIND, 1.4 M ABOVE GROUND LEVEL
THE TOTAL ENERGY EQUIVALENT A-WEIGHTED SOUND PRESSURE : LAeq=49 dB(A)
DATE & TIME OF MEASUREMENT : 7th MAY 1985 01.04 am

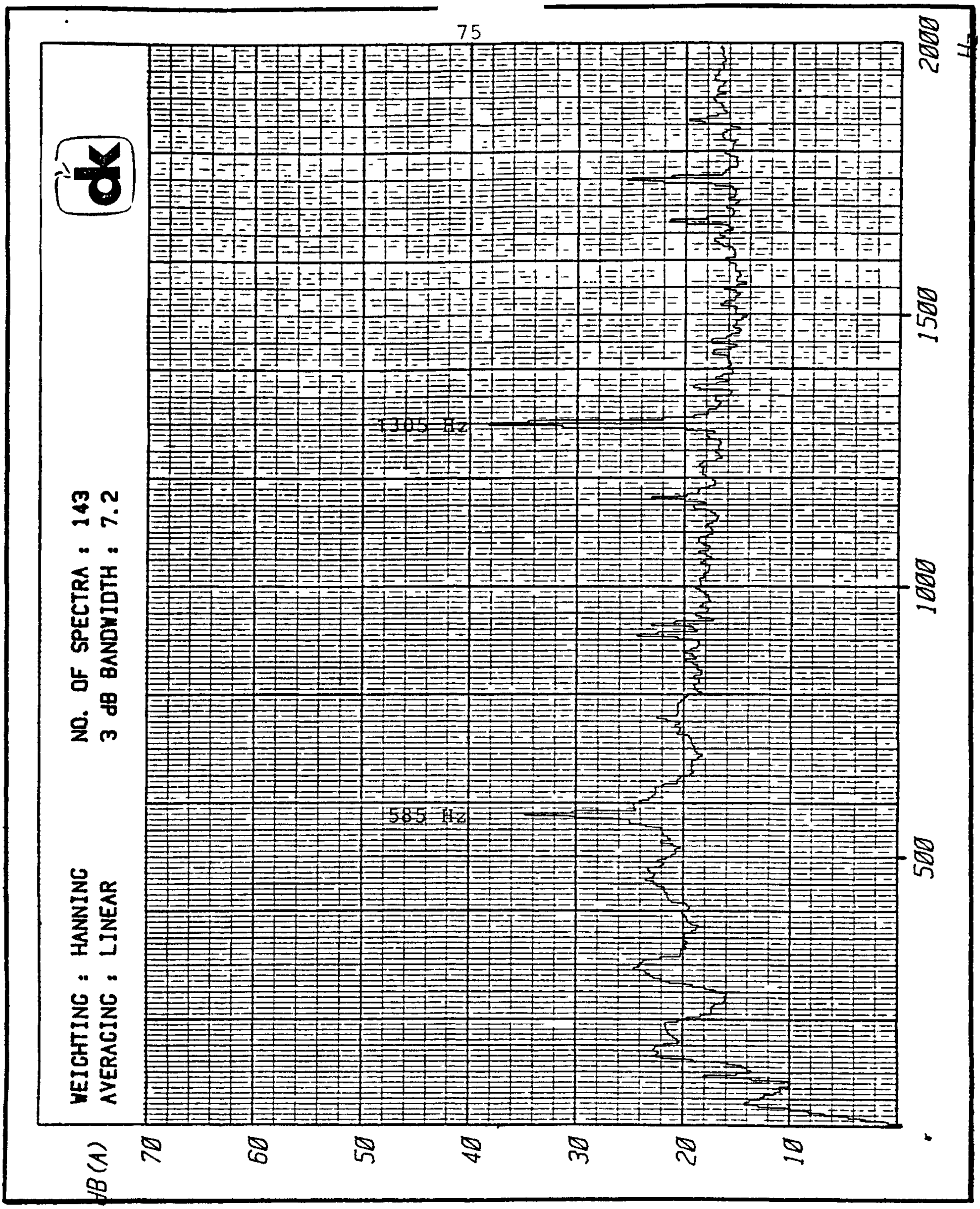
WINDMATIC 17S WINDMILL	RISØ	FIGURE 7



NARROW BAND SPECTRUM ANALYSIS OF THE A-WEIGHTED SOUND PRESSURE LEVEL

MEASUREMENT POINT : 20 METRES DOWNWIND, 1.4 M ABOVE GROUND LEVEL
THE TOTAL ENERGY EQUIVALENT A-WEIGHTED SOUND PRESSURE : LAeq=47 dB(A)
DATE & TIME OF MEASUREMENT : 13th MAY 1985 00.43 midnight

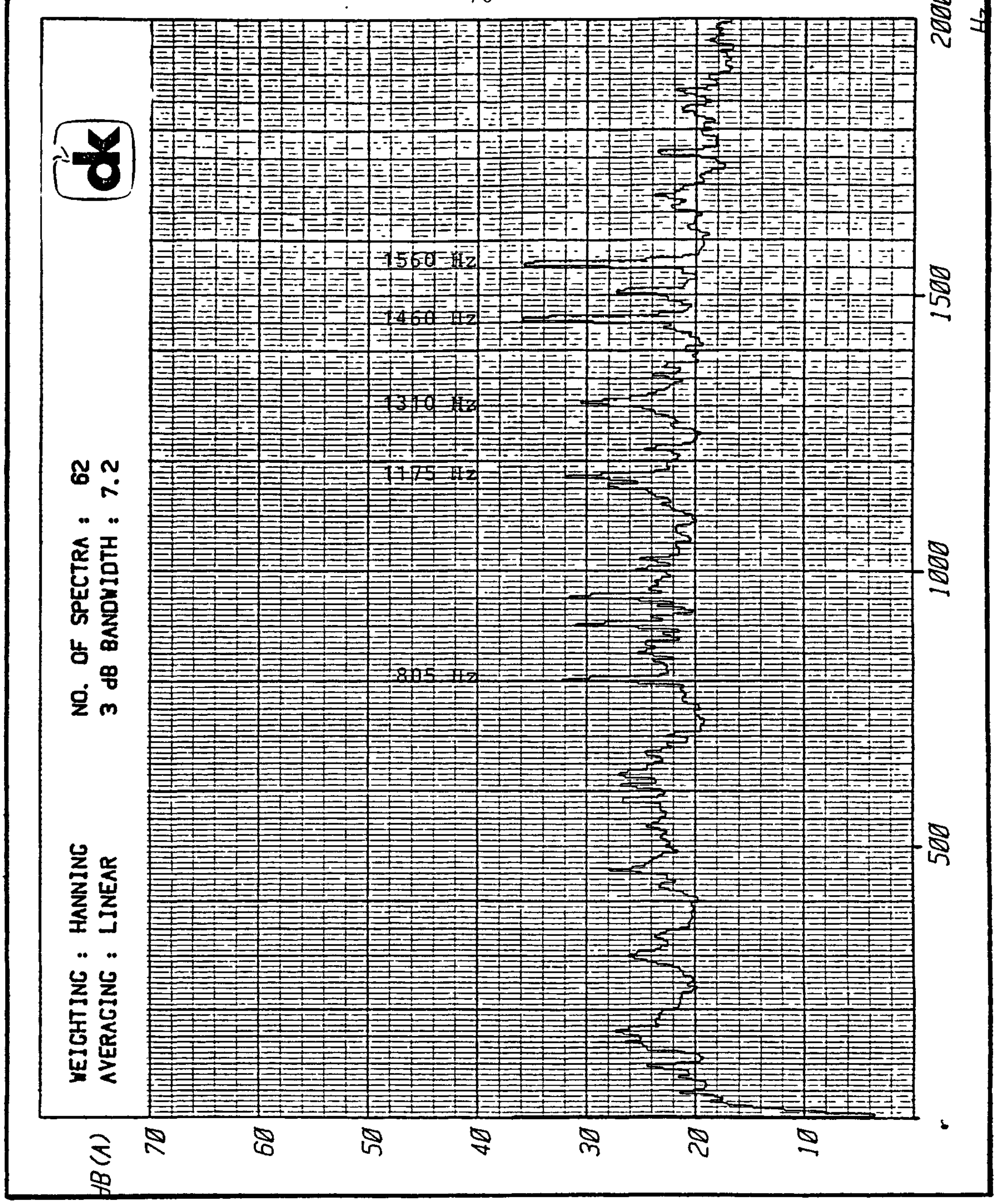
WINDMATIC 17S WINDMILL	RISØ	FIGURE 8



NARROW BAND SPECTRUM ANALYSIS OF THE A-WEIGHTED SOUND PRESSURE LEVEL

MEASUREMENT POINT : 20 METRES DOWNWIND, 1.4 M ABOVE GROUND LEVEL
THE TOTAL ENERGY EQUIVALENT A-WEIGHTED SOUND PRESSURE : LAeq=46 dB(A)
DATE & TIME OF MEASUREMENT : 13th MAY 1985   02.50 am
THE BIG GENERATOR ALONE IN OPERATION.

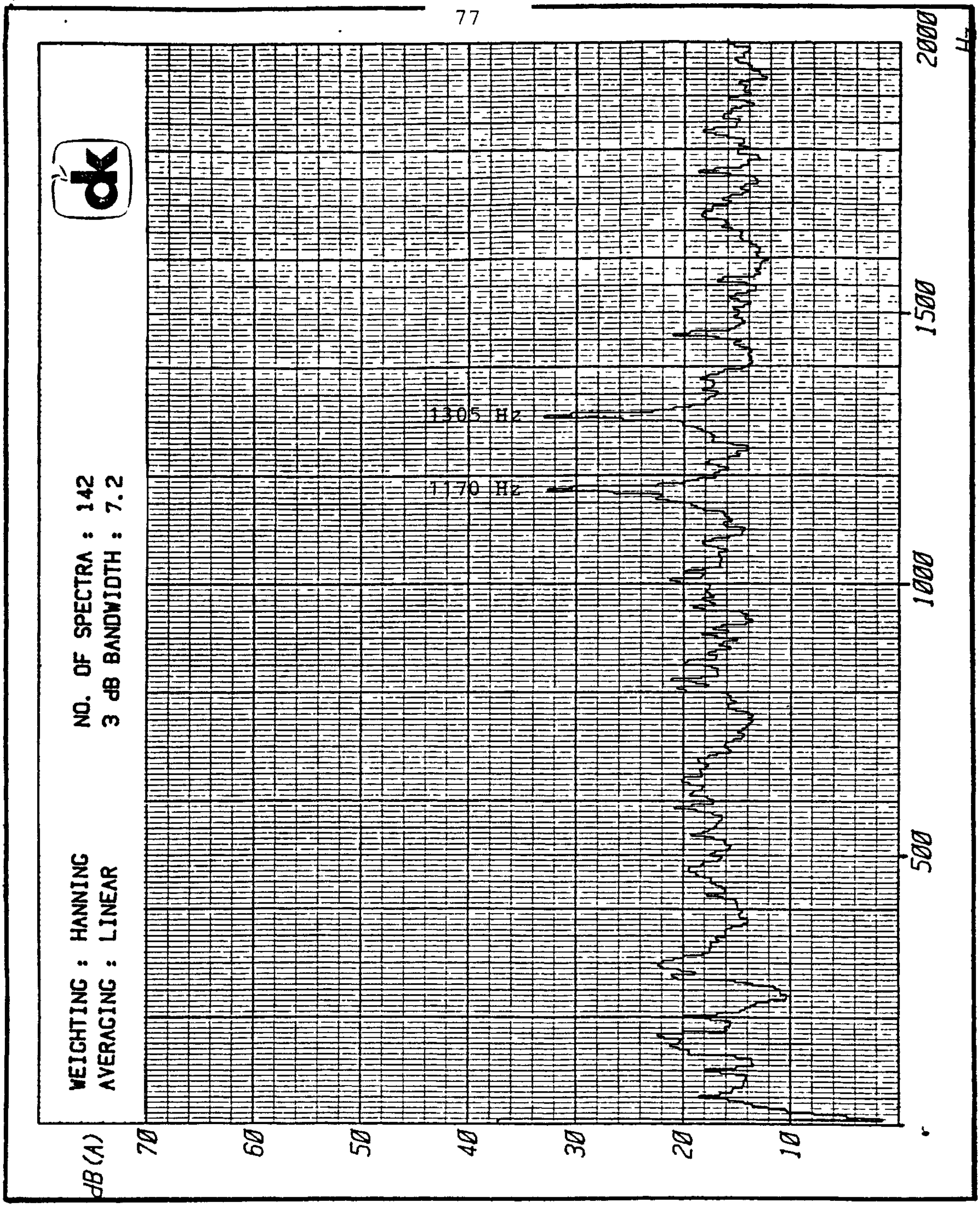
WINDMATIC 17S WINDMILL	RISØ	FIGURE 9



NARROW BAND SPECTRUM ANALYSIS OF THE A-WEIGHTED SOUND PRESSURE LEVEL

MEASUREMENT POINT : 20 METRES PLANE OF ROTATION, 1.4 M ABOVE GROUND
THE TOTAL ENERGY EQUIVALENT A-WEIGHTED SOUND PRESSURE : LAeq=49 dB(A)
DATE & TIME OF MEASUREMENT : 7th MAY 1985 02.58 am

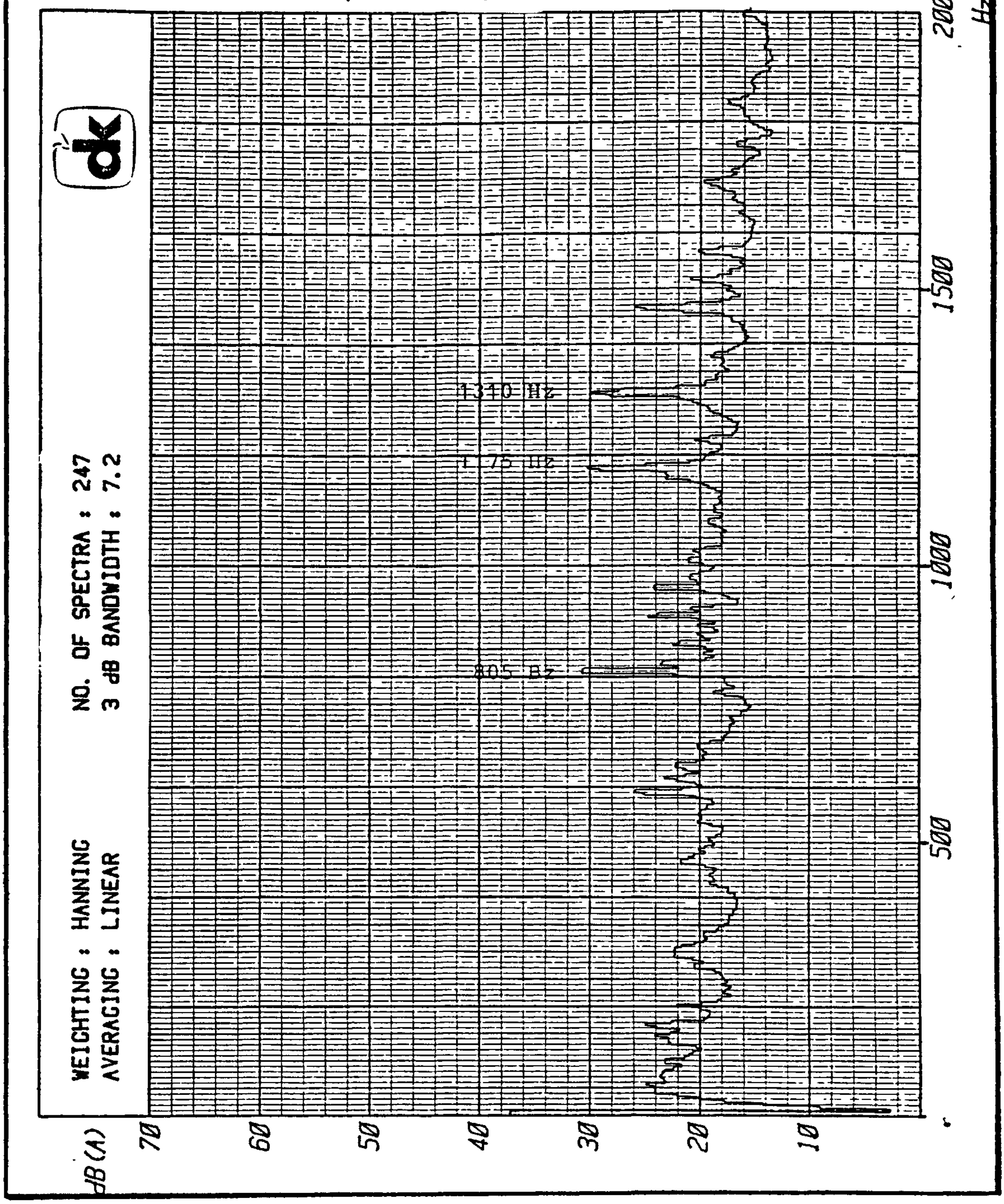
WINDMATIC 17S WINDMILL	RISØ	FIGURE 10



NARROW BAND SPECTRUM ANALYSIS OF THE A-WEIGHTED SOUND PRESSURE LEVEL

MEASUREMENT POINT : 20 METRES PLANE OF ROTATION, 1.4 M ABOVE GROUND
THE TOTAL ENERGY EQUIVALENT A-WEIGHTED SOUND PRESSURE : LAeq=44 dB(A)
DATE & TIME OF MEASUREMENT : 13th MAY 1985 00.22 pm

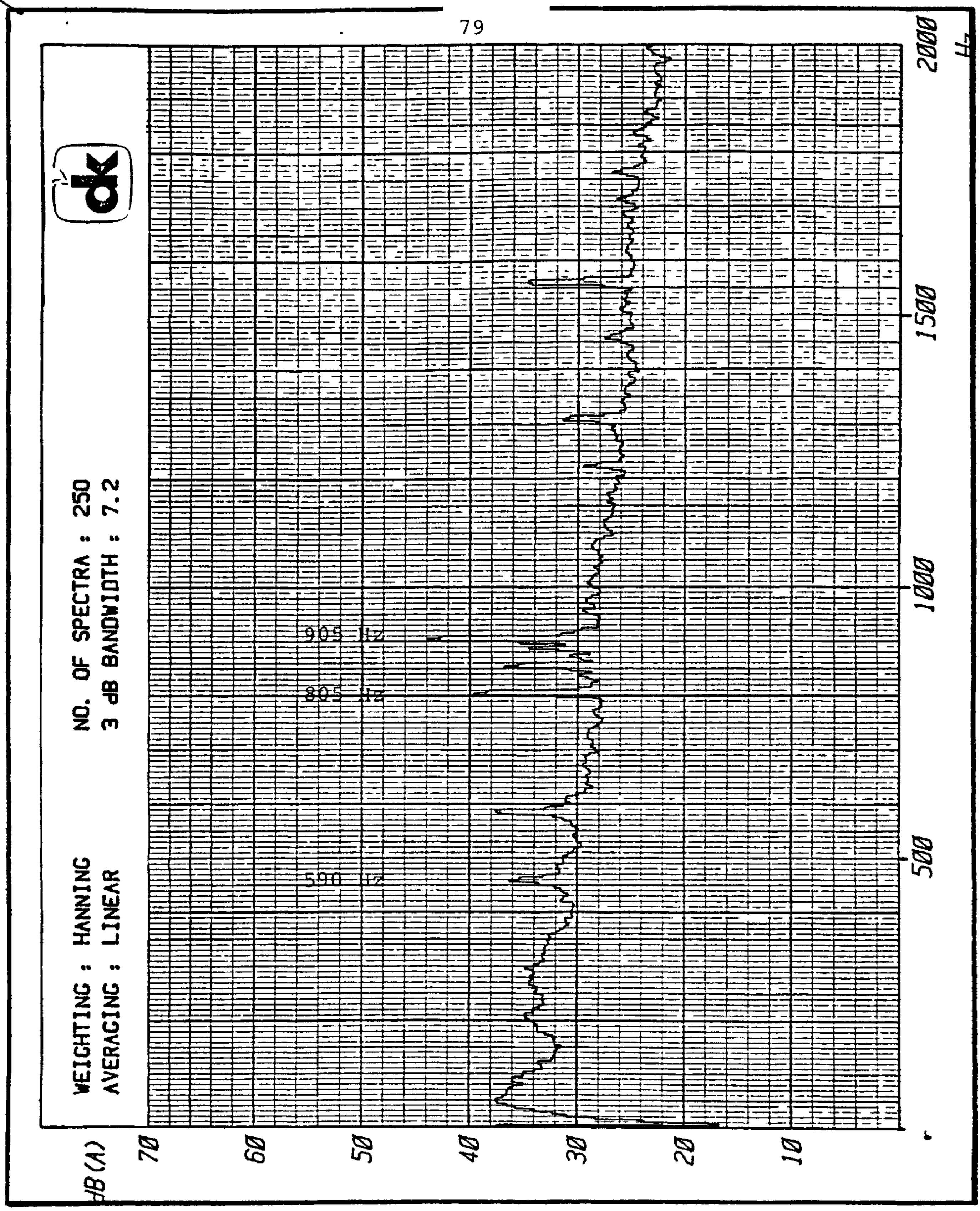
WINDMATIC 17S WINDMILL	RISØ	FIGURE 11.



NARROW BAND SPECTRUM ANALYSIS OF THE A-WEIGHTED SOUND PRESSURE LEVEL

MEASUREMENT POINT : 20 METRES PLANE OF ROTATION, 1.4 M ABOVE GROUND
THE TOTAL ENERGY EQUIVALENT A-WEIGHTED SOUND PRESSURE : LAeq=45 dB(A)
DATE & TIME OF MEASUREMENT : 13th MAY 1985   00.29 pm

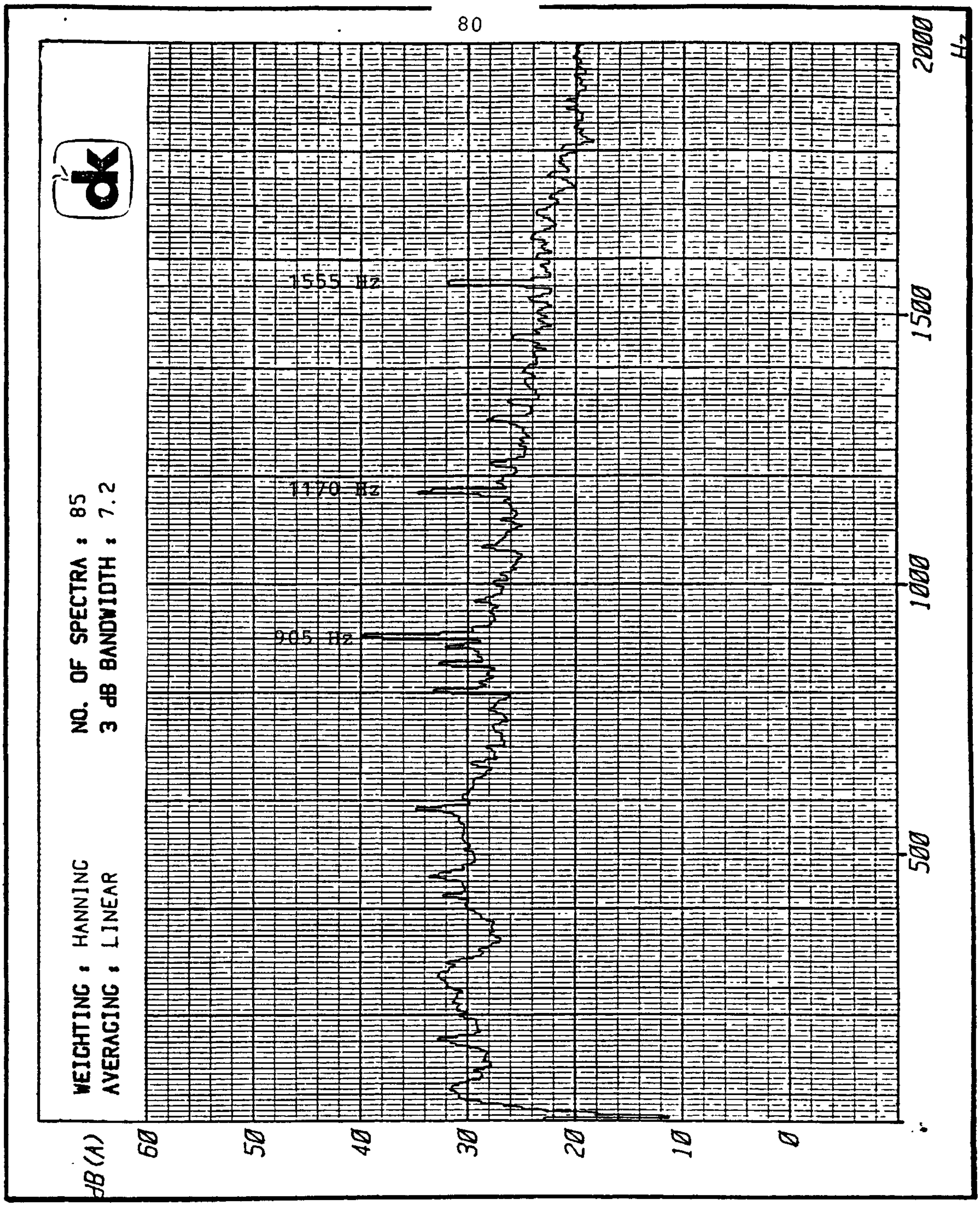
WINDMATIC 17S WINDMILL	RISØ	FIGURE 12



NARROW BAND SPECTRUM ANALYSIS OF THE A-WEIGHTED SOUND PRESSURE LEVEL

MEASUREMENT POINT : 40 METRES DOWNWIND, 1.4 M ABOVE GROUND LEVEL
THE TOTAL ENERGY EQUIVALENT A-WEIGHTED SOUND PRESSURE : LAeq=55 dB(A)
DATE & TIME OF MEASUREMENT : 7th MAY 1985 01.57 pm

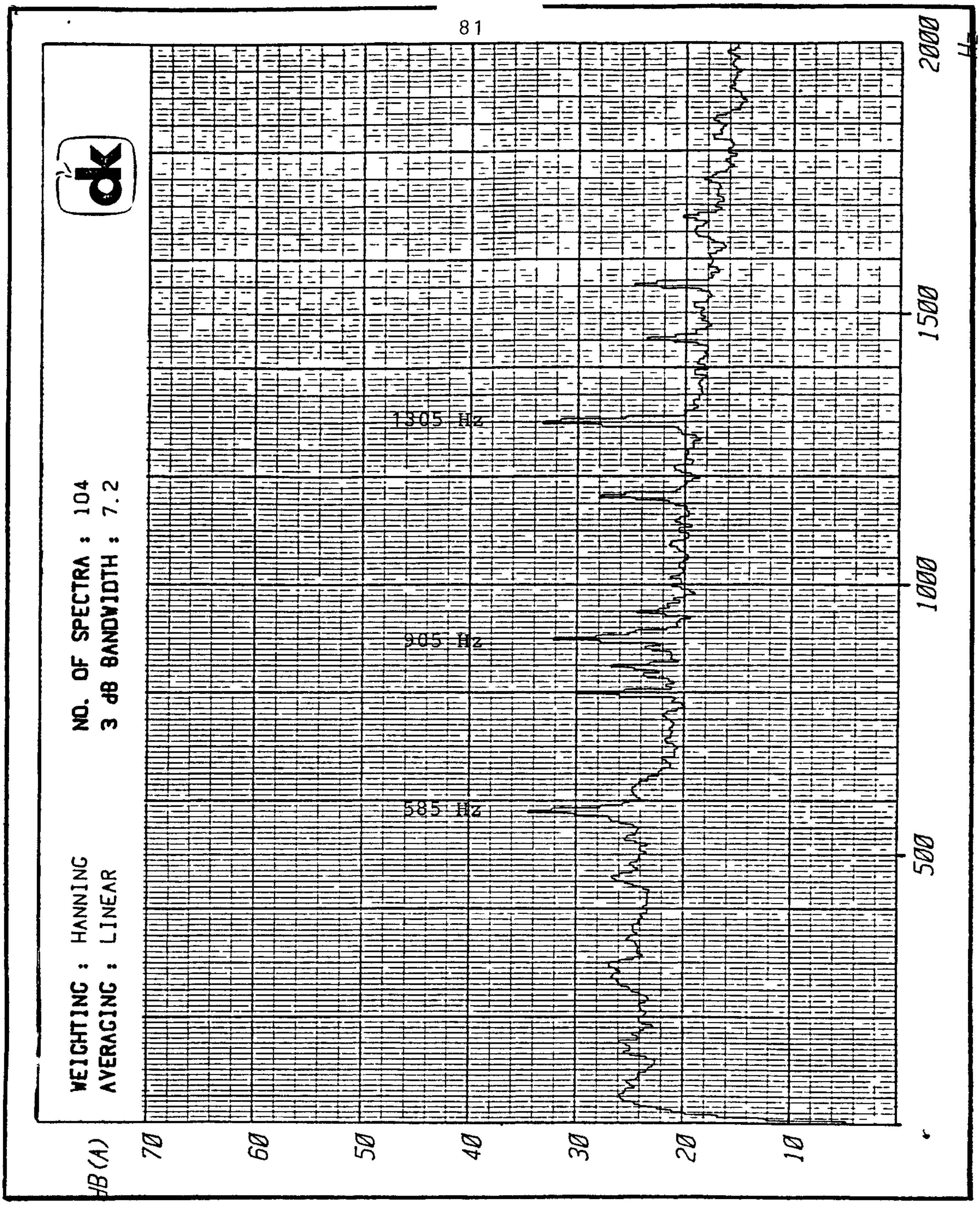
WINDMATIC 17S WINDMILL	RISØ	FIGURE 13



NARROW BAND SPECTRUM ANALYSIS OF THE A-WEIGHTED SOUND PRESSURE LEVEL

MEASUREMENT POINT : 40 METRES DOWNWIND, 1.4 M ABOVE GROUND LEVEL
THE TOTAL ENERGY EQUIVALENT A-WEIGHTED SOUND PRESSURE : LAeq=53 dB(A)
DATE & TIME OF MEASUREMENT : 13th MAY 1985 00.28 pm

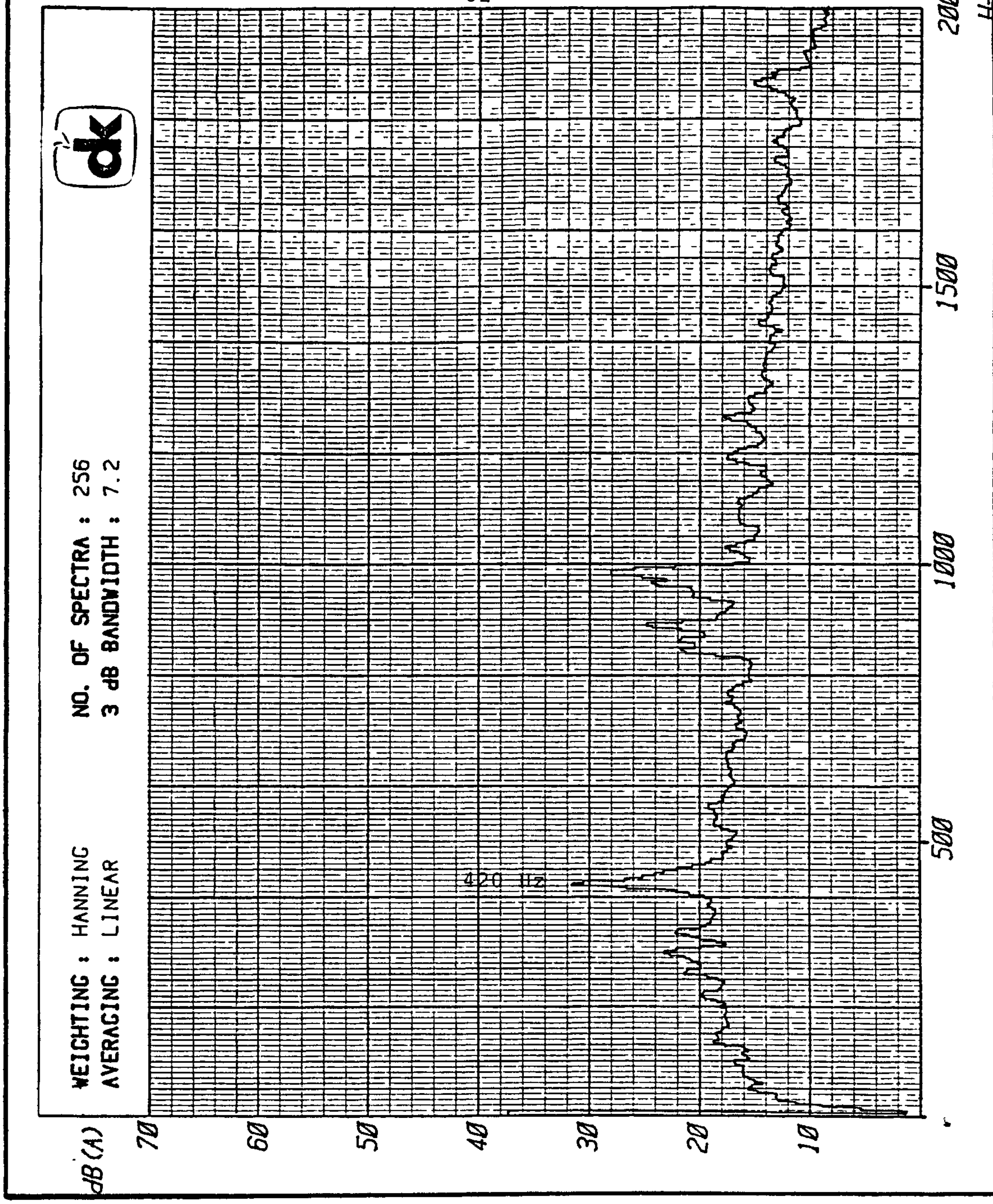
WINDMATIC 17S WINDMILL	RISØ	FIGURE 14



NARROW BAND SPECTRUM ANALYSIS OF THE A-WEIGHTED SOUND PRESSURE LEVEL

MEASUREMENT POINT : 20 METRES DOWNWIND, 3.7 M ABOVE GROUND LEVEL
THE TOTAL ENERGY EQUIVALENT A-WEIGHTED SOUND PRESSURE : LAeq=48 dB(A)
DATE & TIME OF MEASUREMENT : 13th MAY 1985   00.50 pm

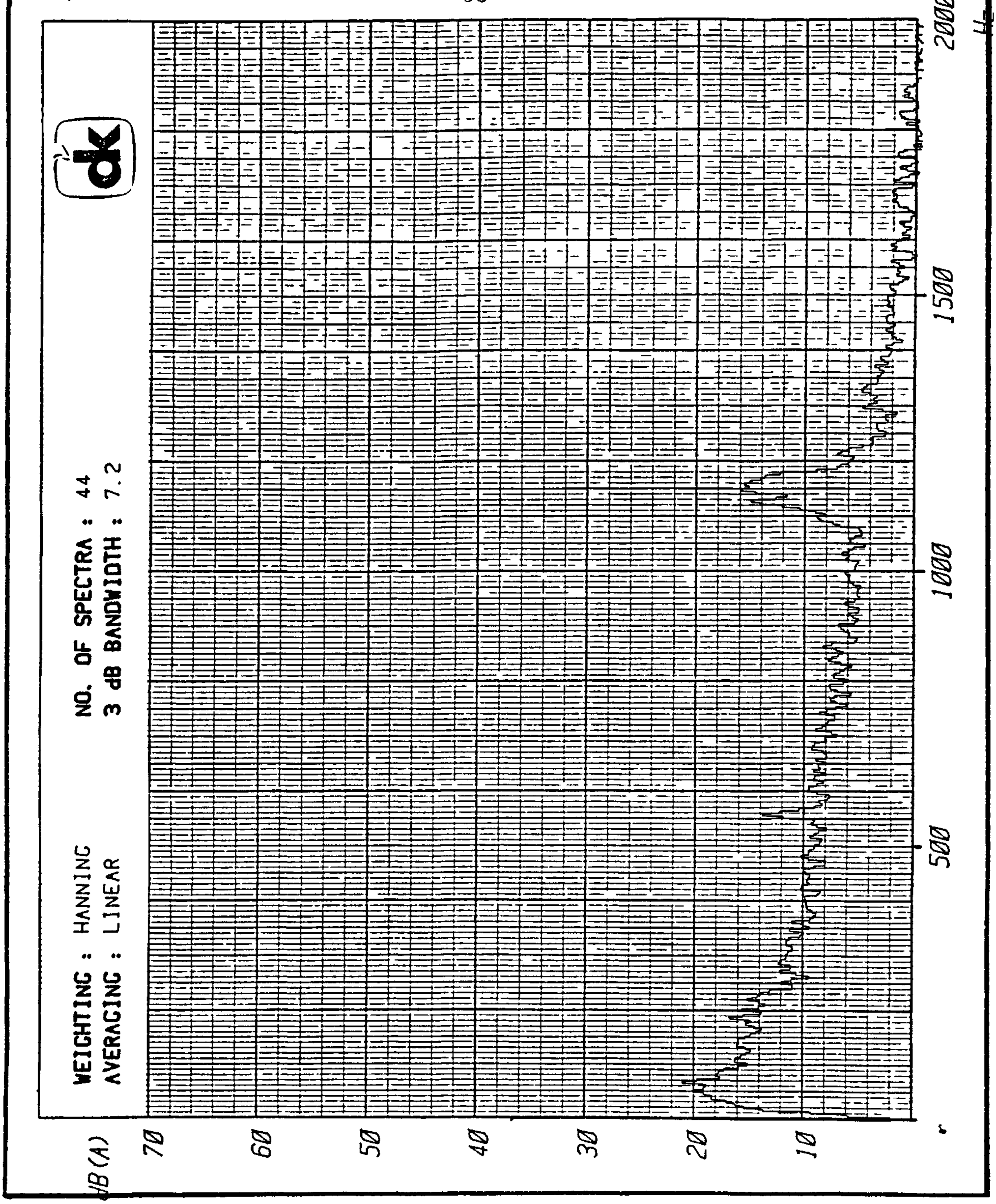
WINDMATIC 17S WINDMILL	RISØ	FIGURE 15



NARROW BAND SPECTRUM ANALYSIS OF THE A-WEIGHTED SOUND PRESSURE LEVEL

MEASUREMENT POINT : 20 METRES DOWNWIND, 3.7 M ABOVE GROUND LEVEL
THE TOTAL ENERGY EQUIVALENT A-WEIGHTED SOUND PRESSURE : LAeq=43 dB(A)
DATE & TIME OF MEASUREMENT : 13th MAY 1985   01.24 am
THE SMALL GENERATOR ALONE IN OPERATION.

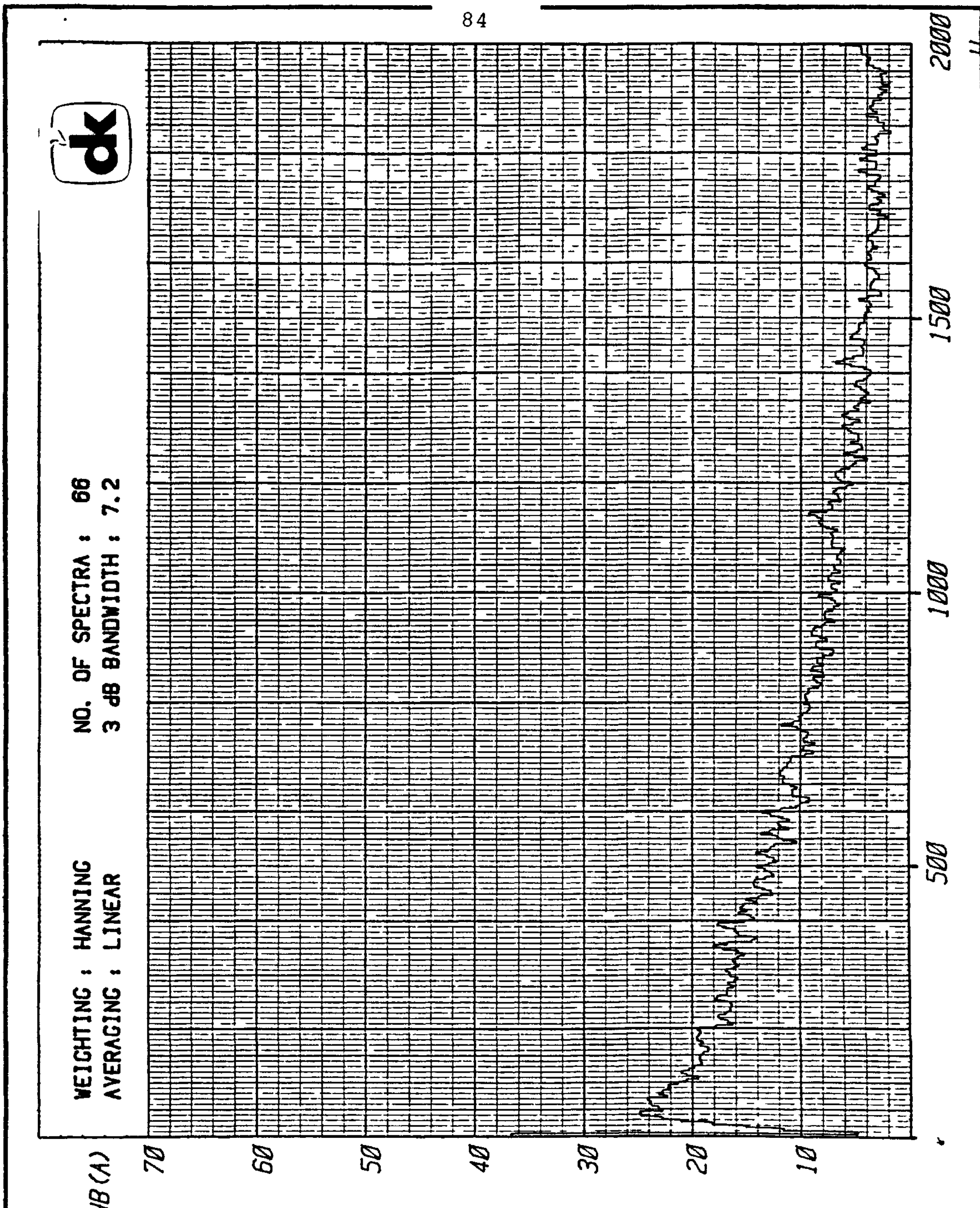
WINDMATIC 17S WINDMILL	RISØ	FIGURE 16



NARROW BAND SPECTRUM ANALYSIS OF THE A-WEIGHTED SOUND PRESSURE LEVEL

MEASUREMENT POINT : 20 METRES PLANE OF ROTATION, 1.4 M ABOVE GROUND LEVEL
THE TOTAL ENERGY EQUIVALENT A-WEIGHTED BACKGROUND SOUND - PRESSURE : L_{Aeq} = 38 dB(A)
DATE & TIME OF MEASUREMENT : 13th MAY 1985   00 36 pm

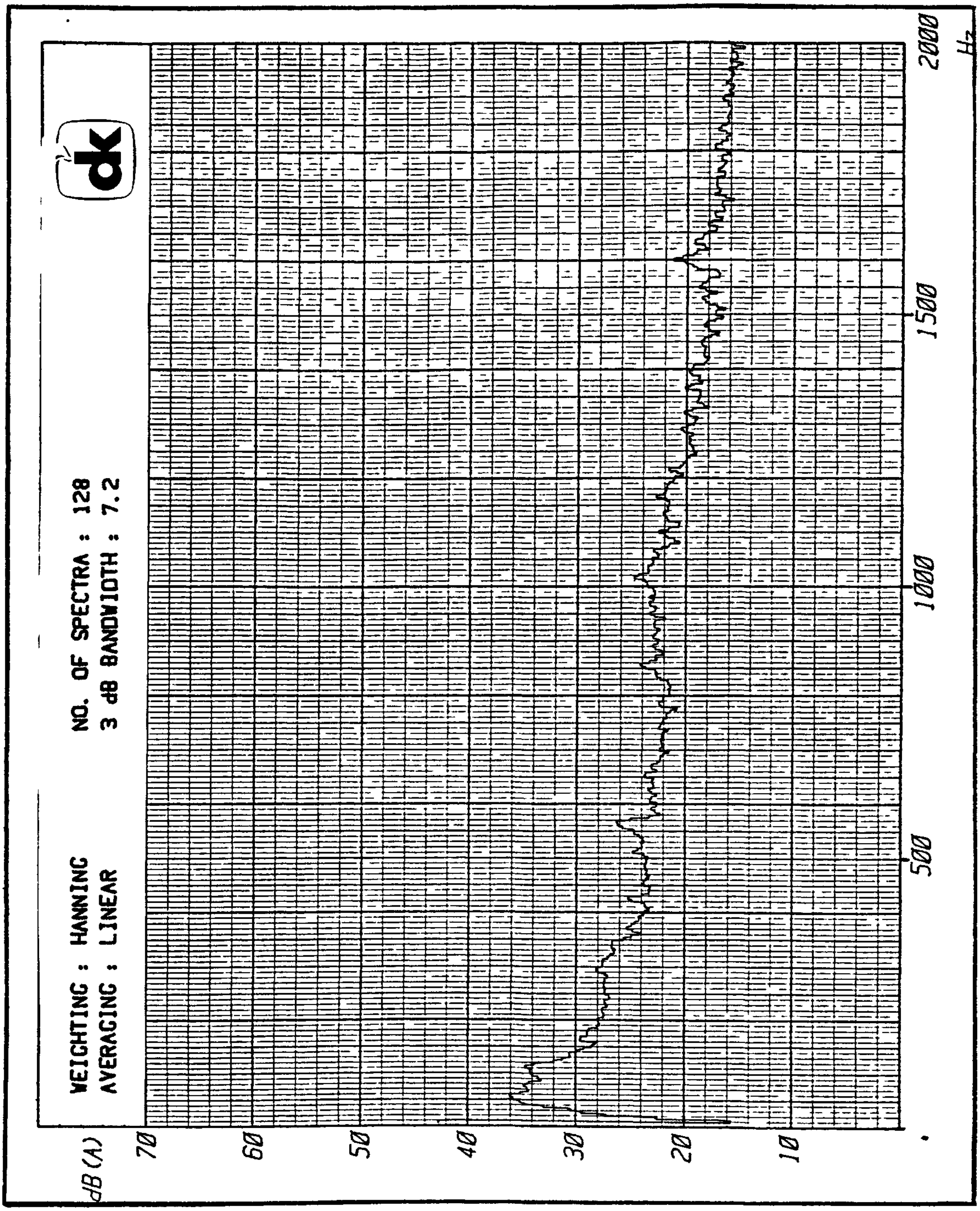
WINDMATIC 17S WINDMILL	*RISØ*	*FIGURE 17*



NARROW BAND SPECTRUM ANALYSIS OF THE A-WEIGHTED SOUND PRESSURE LEVEL

MEASUREMENT POINT : 20 METRES PLANE OF ROTATION, 1.4 M ABOVE GROUND
THE TOTAL ENERGY EQUIVALENT A-WEIGHTED BACKGROUND SOUND -
PRESSURE : L_{Aeq} = 40 dB(A)
DATE & TIME OF MEASUREMENT : 13th MAY 1985   00.52 midnight

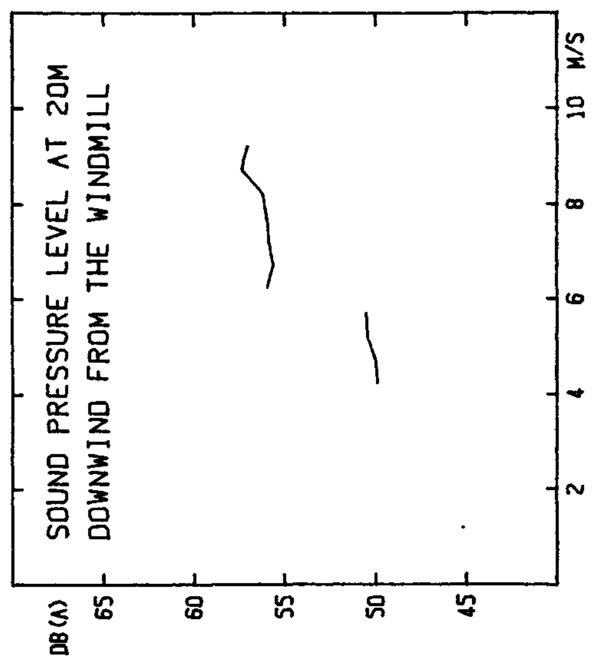
WINDMATIC 17S WINDMILL	RISØ	FIGURE 18



NARROW BAND SPECTRUM ANALYSIS OF THE A-WEIGHTED SOUND PRESSURE LEVEL

MEASUREMENT POINT : 40 METRES DOWNWIND, 1.4 M ABOVE GROUND LEVEL
THE TOTAL ENERGY EQUIVALENT A-WEIGHTED BACKGROUND SOUND - PRESSURE : L_{Aeq} = 50 dB(A)
DATE & TIME OF MEASUREMENT : 7th MAY 1985 01.50 am

WINDMATIC 17S WINDMILL	RISØ	FIGURE 19



THE ENERGY EQUIVALENT A-WEIGHTED SOUND PRESSURE LEVEL FOR INTERVALS OF TWO MINUTES LENGTH VS. WIND VELOCITY 10 METRES ABOVE GROUND LEVEL. MEASUREMENT POINT : 20 METRES DOWNWIND. 1.4 METRES ABOVE GROUND LEVEL.

WINDMATIC 17S WINDMILL	RISØ	FIGURE 20

Risø National Laboratory **Risø - M -** 2546

Risø - M - 2546

Title and author(s)	Date April 1986
WIND TURBINE TEST WIND MATIC WM 17S Troels Friis Pedersen	Department or group The Test Station for Windmills
	Group's own registration number(s)
87 pages + tables + illustrations	

Abstract

The report describes standard measurements performed on a Wind-Matic WM 17S, 75 kW wind turbine. The measurements carried out and reported here comprises the power output, system efficiency, energy production, transmission efficiency, rotor power, rotor efficiency, air-brakes efficiency, dynamical behaviour of the turbine, loads at cut-in and braking, rotor torque at stopped condition, and noise emission.

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